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**FINAL REPORT**

**SPACE SHUTTLE  
AUXILIARY PROPULSION SYSTEM  
DESIGN STUDY  
EXECUTIVE SUMMARY**

**MCDONNELL DOUGLAS ASTRONAUTICS COMPANY - EAST**

**MCDONNELL DOUGLAS**



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AUXILIARY PROPULSION SYSTEM  
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**29 DECEMBER 1972**

**REPORT MDC E0674**

**FINAL REPORT**

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Contract No. NAS 9-12013

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## **ABSTRACT**

This report summarizes the effort conducted in support of the Space Shuttle Auxiliary Propulsion System Design Study and defines the preliminary design of the final selected subsystems. The study was performed for the National Aeronautics and Space Administration under Contract NAS 9-12013.

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## 1. INTRODUCTION

To provide the technology base necessary for design of the Space Shuttle, NASA has sponsored a number of technology programs related to Auxiliary Propulsion Systems (APS). Among such programs has been a series of design studies intended to provide the system design data necessary for selection of preferred system concepts, and to delineate requirements for complementing component design and test programs. The first of these system study programs considered a broad spectrum of system concepts but, because of high vehicle impulse requirements coupled with safety, reuse, and logistics considerations, only cryogenic oxygen and hydrogen were considered as a propellant combination. Additionally, unknowns in thruster pulse mode ignition and concern over the distribution of cryogenic liquids served to eliminate liquid-liquid feed systems from the list of candidate concepts. Therefore, only systems which delivered propellants to the thrusters in a gaseous state were considered for the Reaction Control System (RCS). The results of these initial studies, reported in References A through D, indicated that among the many options for design of a gaseous oxygen/hydrogen system, an approach using heat exchangers to thermally condition the propellants and turbopumps to provide system operating pressure would best satisfy requirements for a fully reusable Space Shuttle. These initial studies focused attention on this general system type but did not examine in depth several viable approaches for turbopump system design and control. To fill this need, NASA contracted with McDonnell Douglas Astronautics Company-East (MDAC-E) in July 1971 for additional study of Space Shuttle Auxiliary Propulsion Systems. This contract (NAS 9-12013), titled "Space Shuttle Auxiliary Propulsion System Design Study," was under the technical direction of Mr. Darrell Kendrick, Propulsion and Power Division, Manned Spacecraft Center, Houston, Texas.

The objective of this study was to develop

design and programmatic data for candidate Space Shuttle RCS in sufficient detail that a valid selection could later be made between the various concepts. As originally defined, the study considered only oxygen and hydrogen propellants. The program was divided into the five phases listed below:

1. Phase A - Requirements Definition
2. Phase B - Candidate RCS Concept Comparisons
3. Phase C - RCS/OMS Integration
4. Phase D - Special RCS Studies
5. Phase E - System Dynamic Performance Analysis

Phase A defined all design and operating requirements for the APS. The result of this phase showed that requirements for the booster and orbiter stages were sufficiently similar to allow concentration of all design effort on the orbiter stage, with the results being applicable to the fly-back-type booster stage as well. These results are documented in Reference E. In Phase B, very detailed design and control analysis for the three most attractive oxygen/hydrogen RCS concepts were conducted. Reference F documents the Phase B results. Phase C evaluated the potential for integration of the RCS with the Orbit Maneuvering System (OMS). Reference G provides documentation of the Phase C oxygen/hydrogen efforts. In Phase D two alternates to gaseous oxygen/hydrogen turbopump RCS were investigated. The results of this phase are documented in Reference H.

According to the initial program plan, Phase E was to analyze the oxygen/hydrogen RCS dynamic response characteristics. However, concurrent with this study, vehicle studies showed that smaller Shuttle orbiters with external, expendable main engine tankage would provide a more cost effective approach than the larger vehicle used to generate baseline requirements in Phase A. This change in vehicle design resulted in a significant reduction in the APS impulse requirements. This effect, together with a

companion Shuttle program decision to allow scheduled system refurbishment, allowed consideration of earth storable propellant systems for auxiliary propulsion. Thus, in November 1971, NASA issued a contract change order to consider monopropellant and bipropellant storable systems. This resulted in a redirection of Phases C and E of the study. Phase C was expanded to include evaluation of candidate storable propellant RCS, with varying degrees of integration with the OMS and the Auxiliary Power Unit (APU). In the redirected Phase E, performance of the most promising storable RCS/OMS/APU options was analyzed. Reference I documents the results of the storable propellant Phase C and E efforts.

Results from the oxygen/hydrogen portion of the study indicated that, for the larger orbiter with internal main tanks, maximum payload weight is obtained with a liquid-liquid oxygen/hydrogen RCS installed integrally within the vehicle. For the smaller

orbiter with external main tanks, installation of the oxygen/hydrogen RCS is practical, but sufficient volume is not available for an oxygen/hydrogen OMS. Thus, the OMS must utilize higher density storable propellants. The high costs associated with the development of oxygen/hydrogen technology were not considered justifiable without application to both the RCS and OMS. Therefore, the oxygen/hydrogen propellants were eliminated from further consideration after the orbiter design change. Consequently, although originally intended to study oxygen/hydrogen systems, the main portion of the study effort concentrated on earth storable propellants.

This report summarizes the tasks conducted in Phases A through E of the Auxiliary Propulsion System Design Study and defines in summary form the final configurations for the alternate propellant configurations, with primary emphasis on earth storable propellants.

## 2. STUDY APPROACH

The Space Shuttle Auxiliary Propulsion System Design Study was conducted in five phases. Reference J provides a detailed program plan for the complete study, and defines the task objectives and their relationship to the overall study. The tasks for the oxygen/hydrogen and earth storable propellants studies are shown in Figure 2-1 in flow chart form. Figure 2-2 defines the program schedule.

Phases A, B, C (RCS/OMS Integration), and D considered oxygen and hydrogen propellants. In Phase A, vehicle requirements were defined. Specifically, engine thrust levels, locations, and number of engines were established. Thruster minimum impulse-bit was determined, based on historic engine data and, in conjunction with deadband requirements, used to establish total impulse for limit cycle operation. Combined with maneuver requirements, this information was used to establish total impulse requirements for the oxygen/hydrogen studies.

Phase B was a continuation of the initial oxygen/hydrogen studies which had identified the following three high value concepts: (1) a series-upstream turbine concept which used the combustion products from a single gas generator to first power the turbopump and then thermally condition the propellants, (2) a series-downstream turbine concept in which the order of gas generator exhaust flow through the heat exchanger and turbine was reversed from that above and, (3) a parallel RCS concept which employed separate gas generators to power the turbopump and heat exchanger. In Phase B, detailed analyses were performed to define preferred controls and optimum system design points for the three RCS concepts. Additionally, steady-state and transient operational characteristics and the effects of system malfunctions were evaluated. Finally, the concepts were compared on the basis of pertinent selection criteria.

The Phase C RCS/OMS integration effort evaluated the integration potential between the oxygen/hydrogen RCS and the Orbit

Maneuvering System (OMS). Integration options ranged from a fully integrated system to a separate system in which only propellant storage was common. Preferred methods were selected and design points were developed for two fully integrated systems, one partially integrated system, and one separate system.

Phase D explored the potential of the two alternate, oxygen/hydrogen RCS concepts listed below:

- (1) Gaseous oxygen/hydrogen systems, with conditioners similar to those of the Phase B candidates, but using alternate means of providing system pressure, e.g., electric or hydraulic motor driven pumps or pneumatic bellows pumps.
- (2) Liquid oxygen/hydrogen systems, which eliminated conditioning equipment entirely and delivered the propellants to the engines in a liquid rather than a gaseous state.

For these two system concepts, the operational characteristics of electric and hydraulic motor driven pumps were evaluated to define system performance. Additionally, a detailed thermal analysis of the liquid system was performed to determine the feasibility of this concept.

In the Phase C earth storable propellants study, effort focused on providing sufficient comparative data on alternate storable propellant concepts to allow selection of the best approaches for the Phase E System Performance Analysis. RCS/OMS/APU integration options were evaluated to determine the proper compromise between performance and operating requirements. Both monopropellant (hydrazine) and bipropellant (nitrogen tetroxide/monomethylhydrazine) concepts were considered. Preliminary baseline designs, reflecting various levels of system integration, served as reference points for detailed design and installation studies and for concurrent studies of APU implementation and advanced pressurization and tankage concepts. From these studies, design concepts were updated and six systems were selected for the Phase E

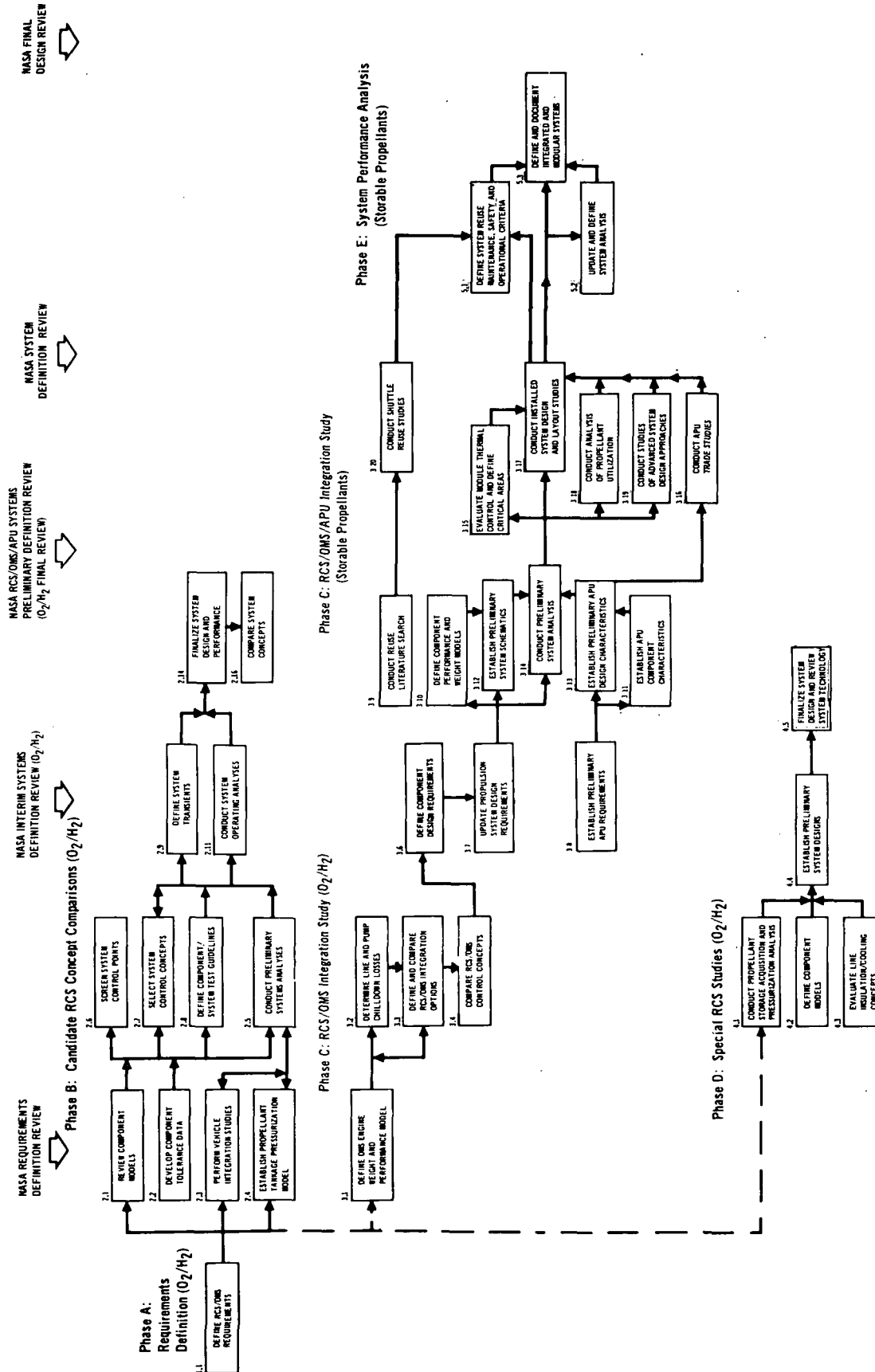


FIGURE 2-1 APS DESIGN STUDY TASK DESCRIPTION FLOW CHART



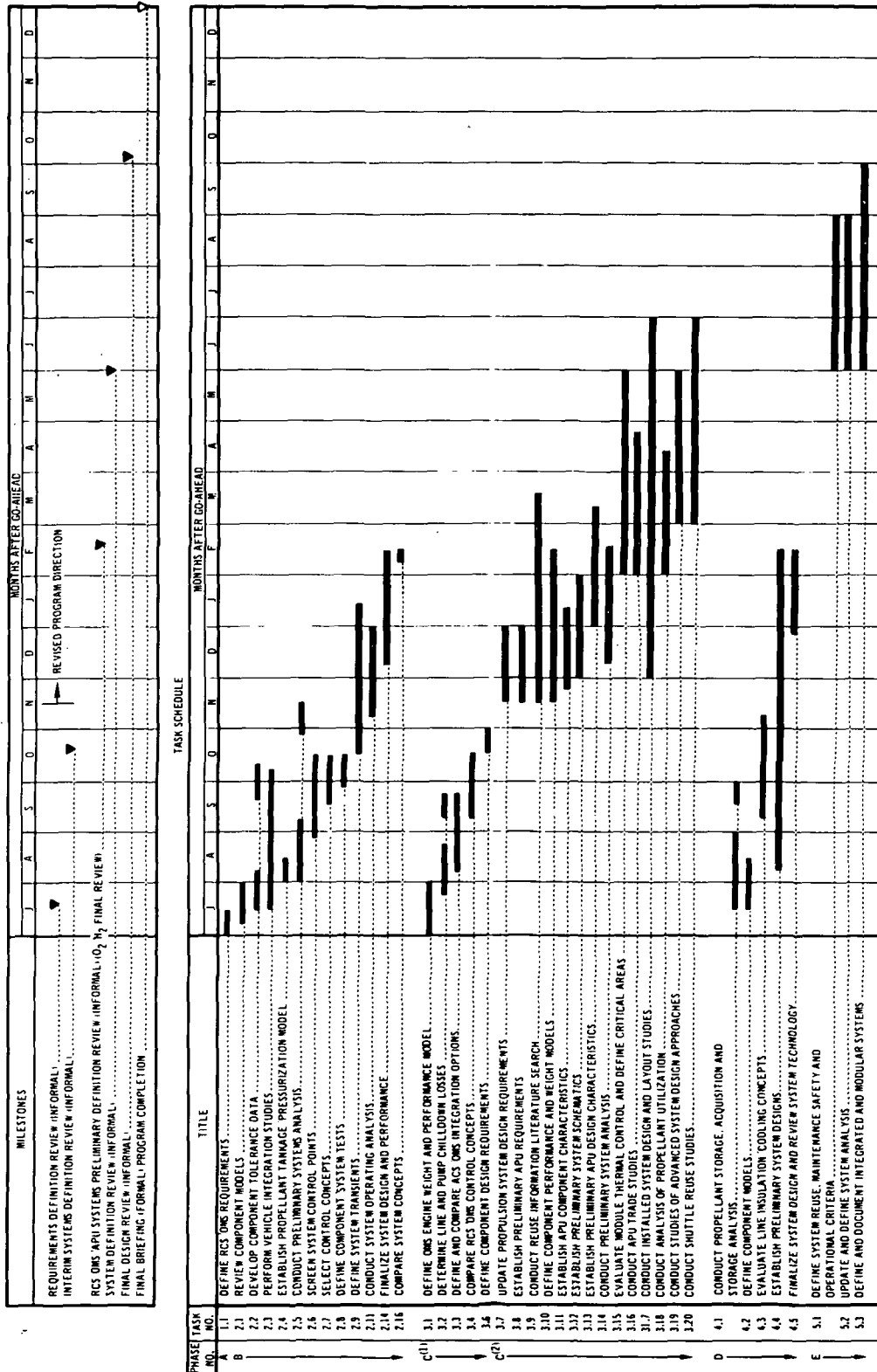


FIGURE 2-2 MASTER SCHEDULE

(1) OXYGEN/HYDROGEN RCS OMS INTEGRATION STUDY  
(2) EARTH STORABLE PROPELLANTS STUDY

final performance analysis. In this phase, system designs and performance were refined, and system reuse, maintenance, safety, and operational criteria were established.

This report summarizes the tasks conducted in Phases A through E of the Auxiliary

Propulsion Design Study. The following sections provide a summary of the alternate oxygen/hydrogen and earth storable systems. Also presented is a description of the designs selected, their operation, and the rationale behind their selection.

### 3. OXYGEN/HYDROGEN STUDIES

The oxygen/hydrogen effort performed in this study was divided into three areas: (1) a further evaluation of turbopump RCS configurations initially studied under Contract NAS 8-26248, (2) an assessment of the integration potential of the RCS and OMS, and (3) an investigation of RCS concepts utilizing power sources other than turbopumps. The sections that follow provide a summary of the results of these investigations.

**3.1 Requirements Definition - Phase A** - RCS thrust level and total impulse were established for the vehicle configuration, design characteristics, and acceleration requirements defined in the Space Shuttle Vehicle Description and Requirements Document (SSVDRD). The distinguishing feature of this orbiter was that the main engine propellant tanks were internal to the vehicle, resulting in a large orbiter stage.

A detailed study was conducted to define APS thrust level, total impulse and number of thrusters. Options available within the constraints imposed by the vehicle acceleration requirements and vehicle configuration were compared to establish the installation and thruster characteristics which would provide minimum RCS weight. A thrust level of 1150 lbf was selected for the RCS thrusters. At this level, 33 RCS thrusters were required. It was also required that the system be capable of sustaining the firing of five thrusters (5750 lbf equivalent thrust). This corresponds to the use of four thrusters for translation and the equivalent of one additional thruster for vehicle attitude control during the maneuver. The total RCS impulse, including both attitude control and vernier translation maneuvers of less than 20 ft/sec was 2.23 million lbf-sec. Axial translation maneuvers in excess of 20 ft/sec were allocated to the Orbit Maneuvering System (OMS). Impulse requirements for three typical missions were defined. Figure 3-1 summarizes the RCS and OMS design requirements.

Several general requirements which apply

to both RCS and OMS design include minimal maintenance with ease of component removal and replacement, a minimum service life of 100 mission cycles over a ten year period with cost effective refurbishment, and seven days of self-sustaining life for each mission. Additionally, the RCS and OMS must provide control for crew safety after the failure of any two critical components, except in the event of an abort caused by a main engine failure. In this case, the OMS must only operate after a single failure since the main engine loss constitutes the first system failure.

	ORBITER	BOOSTER
<b>RCS</b>		
NUMBER OF THRUSTERS	33	24
THRUSTER THRUST (LB)	1,150	1,150
NUMBER OF CONDITIONERS	3	4
SYSTEM THRUST (LB)	5,750	9,200
TOTAL IMPULSE (LB-SEC)		500,000
RESUPPLY	$2.23 \times 10^6$	---
EASTERLY LAUNCH	$2.23 \times 10^6$	---
SOUTH POLAR	$2.15 \times 10^6$	---
	DESIGNED FOR ORBITAL OPERATIONS	DESIGNED FOR ABORT
<b>OMS</b>		
NUMBER OF ENGINES	3	3
ENGINE THRUST (LB)		12,000
SYSTEM THRUST (LB)		24,000
TOTAL IMPULSE (LB-SEC)		
RESUPPLY	$10.34 \times 10^6$	---
EASTERLY LAUNCH	$3.72 \times 10^6$	---
SOUTH POLAR	$12.87 \times 10^6$	---

FIGURE 3-1 RCS/OMS DESIGN REQUIREMENTS

**3.2 Candidate RCS Comparisons - Phase B**  
Three alternate gaseous oxygen/hydrogen RCS configurations were considered in this study phase. These differ in the arrangement of the gas generators, turbopumps, and propellant conditioners, as shown in Figure 3-2. The first concept places the turbine upstream from the conditioner in the gas generator exhaust flow. The second concept reverses the order of the turbine and conditioner. The third concept uses two parallel gas generators, one feeding the turbine and one feeding the conditioner.

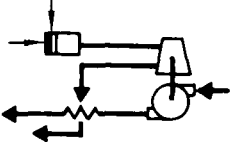
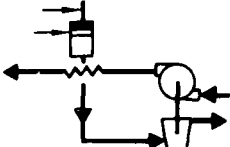
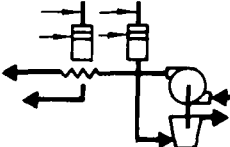
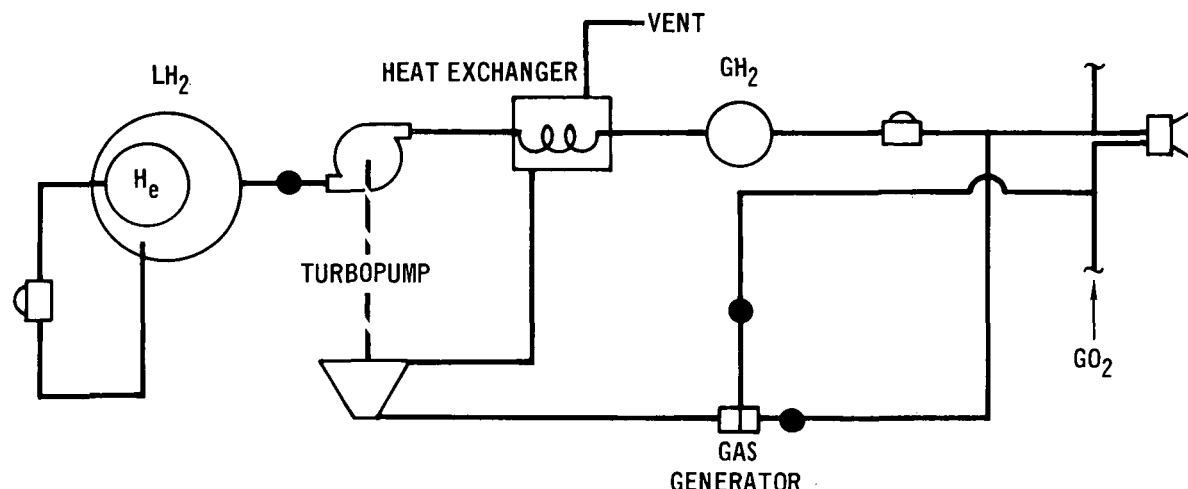
	SERIES TURBINE UPSTREAM 		SERIES TURBINE DOWNSTREAM 		PARALLEL FLOW 	
SYSTEM						
WEIGHT, LBM	10,232		10,348		10,907	
TOTAL IMPULSE, LBF-SEC	2.23M		2.23M		2.23M	
SPECIFIC IMPULSE, SEC	367		366		348	
MIXTURE RATIO	3.12		3.11		2.91	
THRUSTER						
THRUST LEVEL, LBF	1,150		1,150		1,150	
SPECIFIC IMPULSE, SEC	428		428		428	
MIXTURE RATIO	4		4		4	
CHAMBER PRESSURE, LBF /IN <sup>2</sup> A	300		300		300	
GAS GENERATOR	H <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>	O <sub>2</sub>	H <sub>2</sub>	O <sub>2</sub>
COMBUSTION TEMPERATURE, °R	2,000	2,000	2,000	2,000	2,000	2,000
CHAMBER PRESSURE, LBF /IN <sup>2</sup> A	250	250	250	250	250	250
MIXTURE RATIO	1	1	1	1	1	1
HEAT EXCHANGER						
HOT SIDE EXIT TEMPERATURE, °R	800	800	930	870	800	800
COLD SIDE EXIT TEMPERATURE, °R	263	503	253	506	245	466
TURBOPUMP						
FLOW RATE, LBM/SEC	3.80	11.86	3.82	11.88	4.23	12.30
DISCHARGE PRESSURE, LBF /IN <sup>2</sup> A	1,550	1,750	1,330	1,850	1,190	1,570
TURBINE PRESSURE RATIO	2.60	2.10	8.00	2.90	16.7	16.7
ACCUMULATORS						
NUMBER OF CYCLES	50	50	50	50	50	50
VOLUME, FT <sup>3</sup>	42.5	14.1	44.8	14.9	49.5	15.1
MINIMUM PRESSURE, LBF /IN <sup>2</sup> A	571	571	571	571	571	571
SWITCH PRESSURE, LBF /IN <sup>2</sup> A	665	666	665	666	660	661
MAXIMUM PRESSURE, LBF /IN <sup>2</sup> A	1,310	1,555	1,275	1,545	1,200	1,450

FIGURE 3-2 RCS DESIGN SUMMARY

As an example of system operation, consider the turbine upstream concept, shown schematically in Figure 3-3. During system operation, propellants from the cryogenic storage tanks are pumped to high pressure using turbopumps, thermally conditioned to superheated vapors in heat exchangers, and then stored in accumulators. Gaseous propellants are supplied to the film cooled thruster assemblies through pressure regulators. The energy for propellant pressure and temperature conditioning is supplied by combustion

products from bipropellant gas generators. Oxygen and hydrogen propellants are supplied to the gas generators from the accumulators. The accumulators operate in a blowdown mode with accumulator pressure decaying from a maximum value to a switching value. At the switching value, accumulator resupply is initiated. The gas generators are ignited, providing energy to power the turbopump and heat exchanger. Accumulator pressure continues to decay to a minimum value during the conditioner

blowdown/recharge cycle is repeated as many times as necessary to satisfy mission total impulse requirements. Although the accumulators operate over a wide pressure range, propellant flow is regulated to constant supply pressure downstream of the accumulators, maintaining a constant inlet pressure to the thrusters and gas generators.



### FIGURE 3-3 BASIC RCS CONCEPT

exchanger gas inlet temperatures, and was best achieved through modulation of the gas generator oxygen valve. This control provided a large system weight reduction and reduced the operating bands of other critical system parameters, such as conditioned propellant temperature and pump discharge pressure (flow rate). Control of hydrogen conditioned temperature in the two series concepts and both hydrogen and oxygen conditioned temperature in the parallel RCS was selected to provide additional system weight reductions. This control was best achieved by modulating the amount of heat exchanger cold side bypass flow. This bypass was required in the series-upstream turbine RCS (hydrogen conditioner) and parallel RCS (both hydrogen and oxygen conditioners) to preclude  $H_2O$  condensation and icing on the hot side tube walls. It was incorporated in the series-downstream turbine RCS (hydrogen conditioner) for the purpose of conditioned temperature control. The final

All three RCS concepts can be controlled within tight operational limits. Figure 3-4 summarizes the optional control concepts for the three candidate configurations. Gas generator combustion temperature control was necessary to avoid excessive turbine/heat

system control provided for modulation of the gas generator  $H_2$  valve in response to pump discharge pressure. This control provided only a modest system weight benefit, but it provided excellent control of heat exchanger cold side inlet conditions and turbopump

power, minimizing the development risk associated with these assemblies. Heat exchanger cold side flow instability has been encountered in previous development programs, and its potential for occurrence is reduced with tight control of inlet conditions.

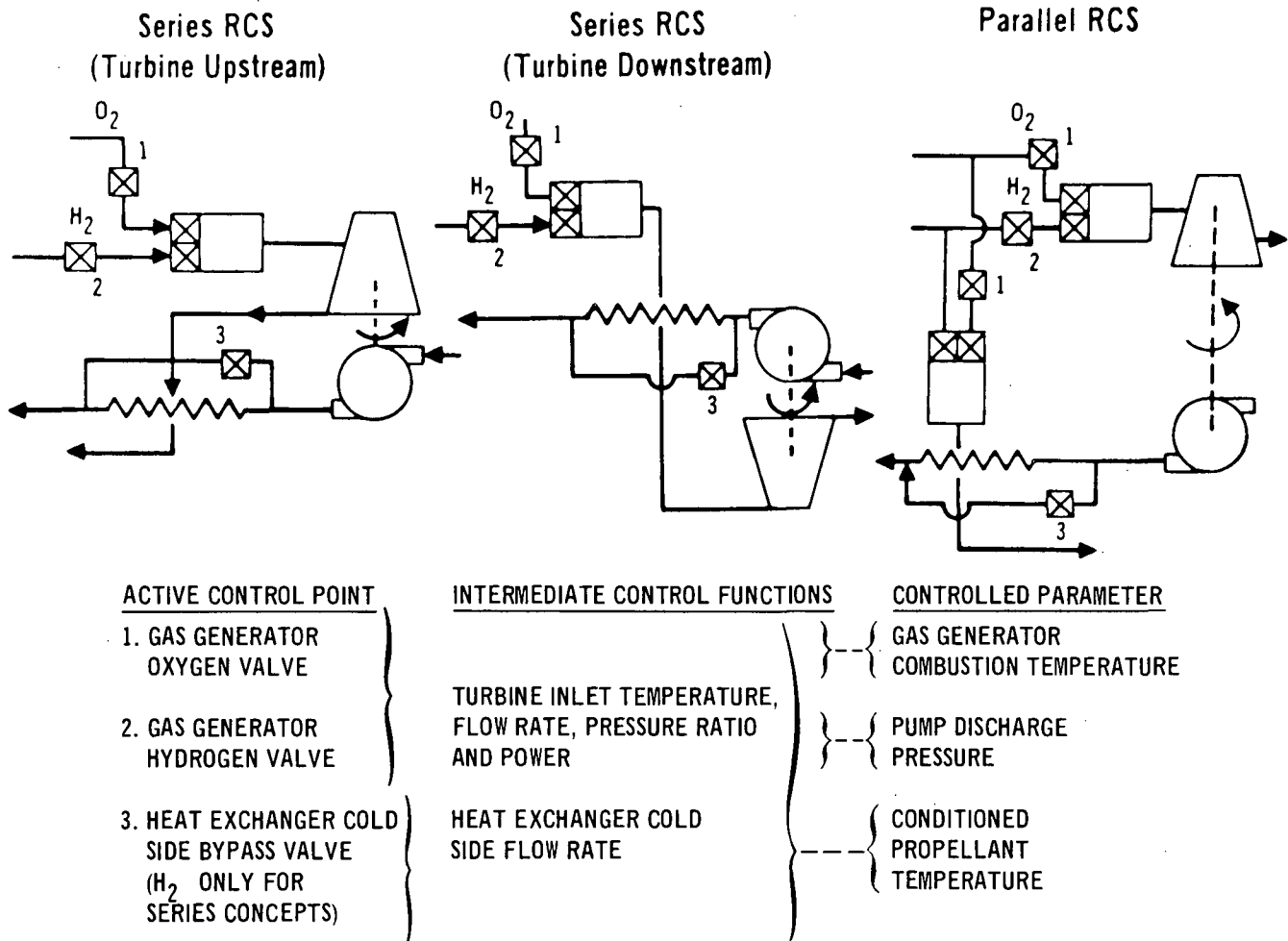


FIGURE 3-4 CONTROL POINT SUMMARY

The three RCS concepts were compared on the basis of weight, complexity, flexibility, reliability, and technology considerations. The two series concepts rated even, ranking higher overall than the parallel RCS. A choice between the two series concepts depends on the Shuttle development philosophy. The upstream turbine RCS affords the lowest weight and volume, but the system requirements must be firmly established at the program outset. Attempts to improve the system

performance at a later date for a second generation vehicle would lead to a complete conditioner redesign due to the turbine inlet temperature restrictions. The series-downstream turbine RCS can be uprated by increasing gas generator combustion temperature and reconfiguring only the heat exchanger for the correspondingly higher hot side inlet temperature.

Several technology concerns were identified during the course of the study. Among these

was the high conditioner cycle life requirement of 5000 cycles (50 cycles per mission for 100 missions) which is a significant extension over the demonstrated life capabilities of current turbopump and heat exchanger designs. In addition, transient conditioner startup analyses showed that turbopump shaft accelerations on the order of 165,000-200,000 RPM/sec can be expected. Since current experience with propellant-cooled bearings is approximately 40,000 RPM/sec, pump bearing design must be regarded as a critical technology area.

**3.3 RCS/OMS Integration Study-Phase C-** During this portion of the APS Design Study, all viable oxygen/hydrogen RCS/OMS integration configurations were compared. The RCS baseline configuration for this study phase was the parallel flow concept. The OMS uses liquid propellant engines fed from a propellant storage assembly. The degree of integration varied from a fully integrated RCS/OMS with common turbomachinery, gas generators, and heat exchangers to a separate system with common propellant tankage only.

Preliminary screening resulted in the selection of four candidate concepts. The selected configurations were two fully integrated systems, one partially integrated system, and a separate system. Fully integrated systems utilize common turbopumps to supply liquid propellants to the OMS engines, and gaseous propellants to the RCS thrusters via the heat exchangers and accumulators. In the partially integrated system, the RCS and OMS are provided dedicated gas generators and turbopumps, which are powered by oxygen and hydrogen propellants stored in common accumulators. In the separate system, the propellant tankage is the only RCS/OMS interface.

The fully integrated system is attractive due to hardware commonality. However, associated problems include OMS and RCS mixture ratio differences, RCS accumulator resupply during OMS operation, and controls for propellant sequencing to the OMS engines. Mixture ratio differences were resolved by using either an extra oxygen pump

for the OMS operation or by utilizing bilevel operating pumps. The remaining problems are alleviated at reduced levels of integration.

Hardware commonality can be implemented in the partially integrated system by using a common-design turbopump capable of bilevel operation. The bilevel turbopumps are designed for the OMS requirements and operate off-design for the RCS. For both fully and partially integrated systems, the recommended method of providing accumulator makeup propellant during OMS operation is with a separate, small heat exchanger/gas generator unit sized to condition only the accumulator makeup gas. This option requires the development of an additional component, but is the preferred approach since it minimizes the number of RCS conditioner cycles.

Separating the RCS and OMS completely except for common propellant storage eliminates integration concerns, but does require different component designs. In the separate RCS/OMS, a staged combustion cycle OMS engine is recommended.

At the lower velocity requirements of the easterly launch mission, the candidate RCS/OMS systems were all weight competitive. At the higher velocity increment (2000 fps), the separate RCS/OMS system is the most attractive.

**3.4 Special RCS Studies - Phase D -** Two alternatives to the turbopump gaseous oxygen/hydrogen systems discussed in Section 3.2 were evaluated. The first alternative maintained the same basic approach as the turbopump systems but used a high pressure liquid accumulator with a small pump, thereby reducing pump power requirements to levels where power sources other than hot gas turbines could be considered. Eliminating the turbopump avoided the technology concerns associated with turbopump bearing life in an environment requiring many rapid startups per mission.

The second alternative also used a liquid accumulator in conjunction with a low power pump but considered distribution of oxygen and hydrogen as liquids to engines which had the capability for liquid propellant ignition.

The "liquid" concept thereby eliminated the need for gaseous accumulators and thermal conditioning equipment. The following paragraphs summarize the evaluation of these two alternatives.

**3.4.1 Alternate Gaseous Oxygen/Hydrogen Systems** - The gaseous systems evaluated as alternates to the turbopump systems are illustrated in Figure 3-5. The most fundamental approach is a fully pressurized system. However, the weight penalty for full pressurization of both the hydrogen and oxygen is severe (5000 lbm).

The use of hydraulic or electric pumps reduces the weight penalties that occur with full pressurization. The number of pump

cycles are minimized through the use of liquid accumulators installed downstream of the pumps. Power for pump drive is provided by the APU. The motor driven pump systems are weight competitive with the reference turbopump system. Their principal drawback is their dependence on APU operation and the increased number of APU starts incurred. Additionally, power requirements are in excess of other APU requirements and higher capacity APU's would be required.

System power requirements can be significantly reduced at constant system weight through the use of a hydraulic hybrid system. The oxygen side of this system is fully pressurized, whereas a hydraulic motor pump - liquid accumulator configuration is employed

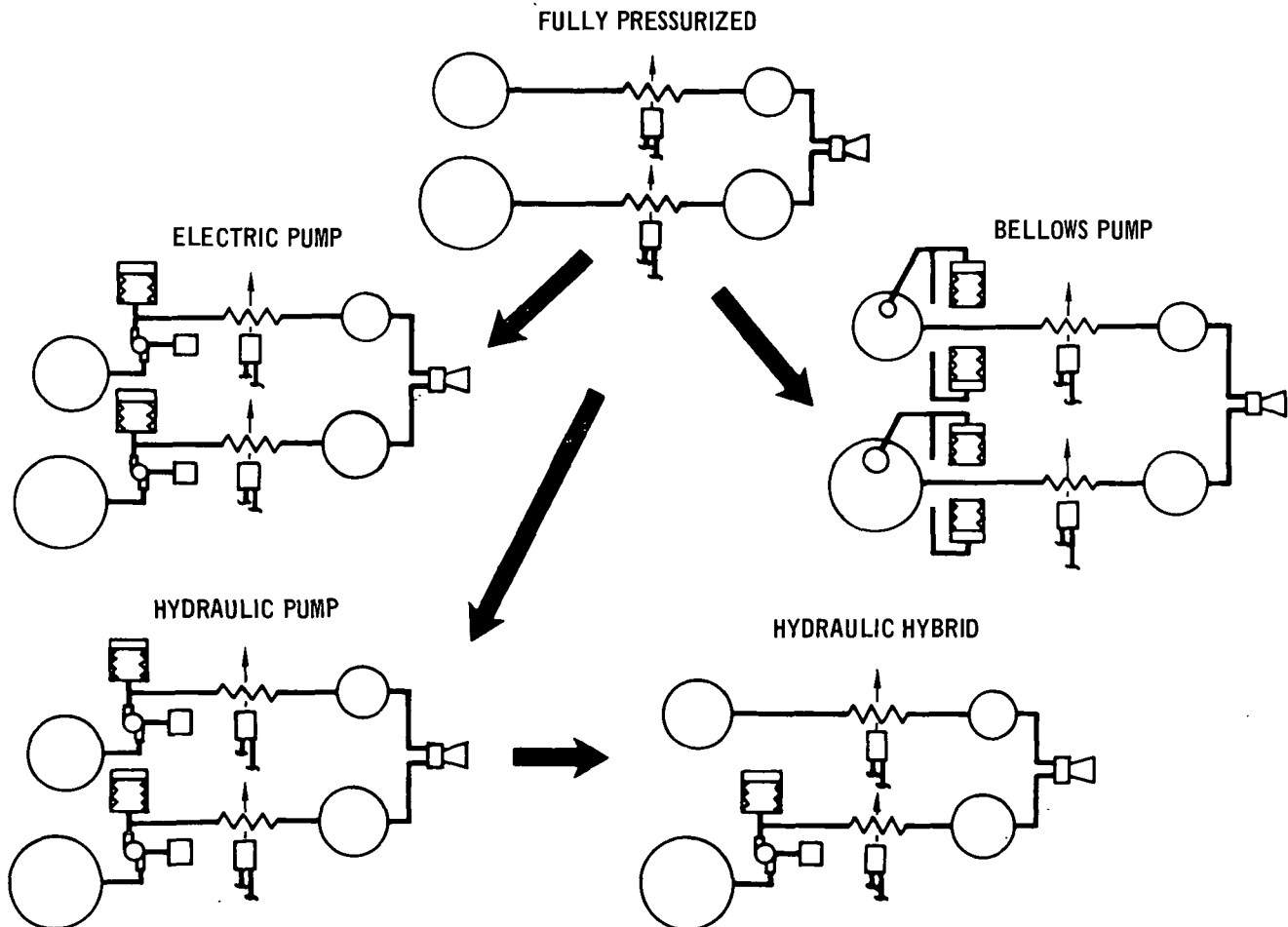


FIGURE 3-5 GASEOUS O<sub>2</sub>/H<sub>2</sub> CONCEPTS



for the hydrogen. The use of fully pressurized oxygen results in some weight penalty, but since oxygen accounts for less than 20% of the total propellant volume, this penalty is small, and allows simplification of system design and development.

Pump dependence on APU operation can be completely eliminated with the use of bellows pumps. System controls are such that when one liquid accumulator is depleted, its pressurant is vented and refill is provided under the storage tank pressure head. The use of heated helium pressurant to minimize vent losses results in a weight competitive system.

**3.4.2 Liquid Oxygen/Hydrogen Systems -** Liquid oxygen/hydrogen RCS concepts were evaluated to determine the feasibility of distributing liquid propellants to the engines. This approach would allow removal of the gas generators, propellant heat exchangers, and gaseous accumulators, as depicted in Figure 3-6. The particular configuration illustrated is but one of a generic series derived from the basic turbopump RCS. In addition to advantages in system simplicity, the liquid concept offers a large system weight reduction by eliminating the heavy gaseous accumulators and by avoiding gaseous propellant conditioning losses.

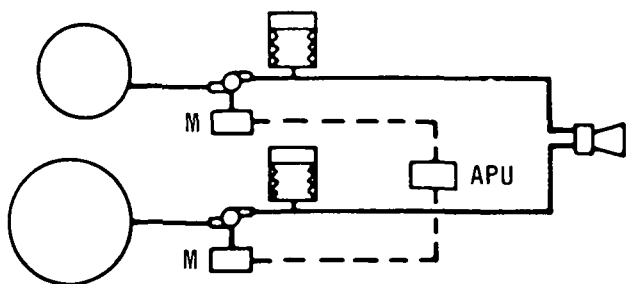
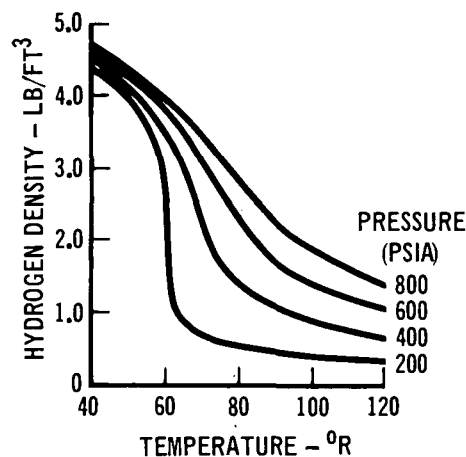


FIGURE 3-6 LIQUID - LIQUID CONCEPT

Liquid cryogenic systems were not considered in previous studies due to concerns associated with propellant heating in a large, relatively complex distribution system and because of concerns with engine pulse mode ignition. Figure 3-7 illustrates these concerns. Although the ignition temperature limits are

significantly lower than those previously considered, a review of ignition phenomena with engine manufacturers showed liquid ignition to be feasible. A thorough investigation of propellant heating was also performed to evaluate the feasibility of liquid propellant distribution.

**FEED SYSTEM DESIGN -**  
COULD A PRACTICAL DISTRIBUTION SYSTEM BE DESIGNED AND WOULD THAT DESIGN PROVIDE SUFFICIENTLY LOW PROPELLANT HEATING LEVELS FOR ENGINE OPERATION?



**ENGINE IGNITION -**  
WAS LIQUID IGNITION FEASIBLE IN A PULSE MODE ENGINE?

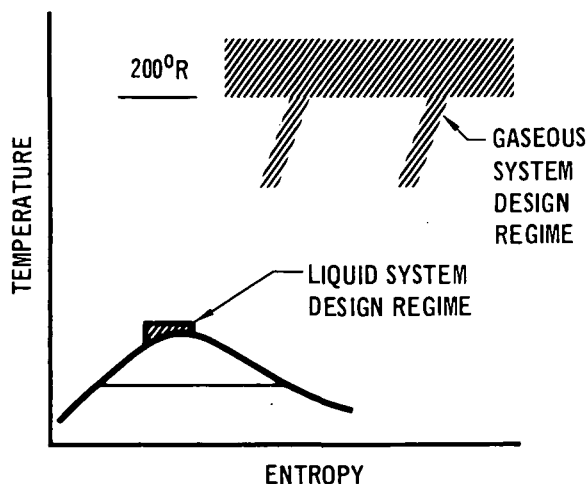


FIGURE 3-7 PREDOMINANT LIQUID SYSTEM QUESTIONS

The primary consideration in the distribution of liquid cryogenics is the minimization of heat input to preclude propellant vaporization and large density changes. For this study, the hydrogen was delivered supercritically, thereby ensuring single phase flow. Variations in hydrogen density were found to be more critical than oxygen density variations, and a maximum hydrogen temperature of 65°R was established to maintain acceptable engine performance. A system thermal model was assembled and an analysis performed to determine the implications of this hydrogen temperature constraint. The model incorporated vacuum jacketed lines with high performance insulation (HPI) between the inner and outer lines, and thruster thermal standoffs, similar to those commonly employed for hydrazine engines.

Propellant utilization in limit cycle operation serves to balance heat input and output, and steady state temperatures below the 65°R temperature limit are achieved for vehicle deadbands of 8 degrees or less. This analysis verified that thermal management of liquid propellants in the APS distribution system is feasible if proper attention is given to thermal insulation and isolation of major heat inputs, such as thruster heat soakback.

Having established the feasibility of the liquid system concept, the remainder of the liquid study effort was devoted to design and sizing considerations. Based on the gaseous studies described in Section 3.4.1, a hybrid system, using fully pressurized oxygen and pumped hydrogen, was selected as the baseline concept. Trade studies were conducted to determine the most attractive pump and pump driver concepts. The preferred approach, based on considerations of weight and simplicity, was determined to be a centrifugal pump driven by a hot gas

turbine of the same general type used for the gaseous systems. A liquid system turbopump would present considerably less technology risk than a gaseous system turbopump since, with liquids, the accumulator can be sized to provide acceptable shaft acceleration and increased bearing life for a minimal weight increase. In addition, the liquid system can accommodate a wider range of pump performance, and it would be much easier to integrate the pump into the system than in a gaseous system where pump performance can affect operation of the propellant heat exchangers.

The results of this study suggest two approaches to the evolution of a high performance system. Figure 3-8 shows these approaches. One approach starts with a gaseous hydrogen-liquid oxygen system. The system uses liquid oxygen because the weight penalties associated with avoidance of oxygen pumps are small and distribution of liquid oxygen was found to be feasible. Gaseous hydrogen is used because the engine ignition requirements are state-of-the-art, similar to the Pratt and Whitney RL-10 engine. This gaseous system could be upgraded by either increasing the gas generator operating temperature, thereby increasing system efficiency, or by utilizing a liquid turbopump system which eliminates the gas generator and gaseous accumulator. The decision as to which means of improvement was most attractive could be made on the basis of the relative status of technology demonstration programs in the areas of liquid ignition and high temperature heat exchangers.

The second approach shown in Figure 3-8 starts with a simple, fully pressurized liquid-liquid system; later a turbopump and liquid accumulator could be added to the hydrogen side providing a high performance design.

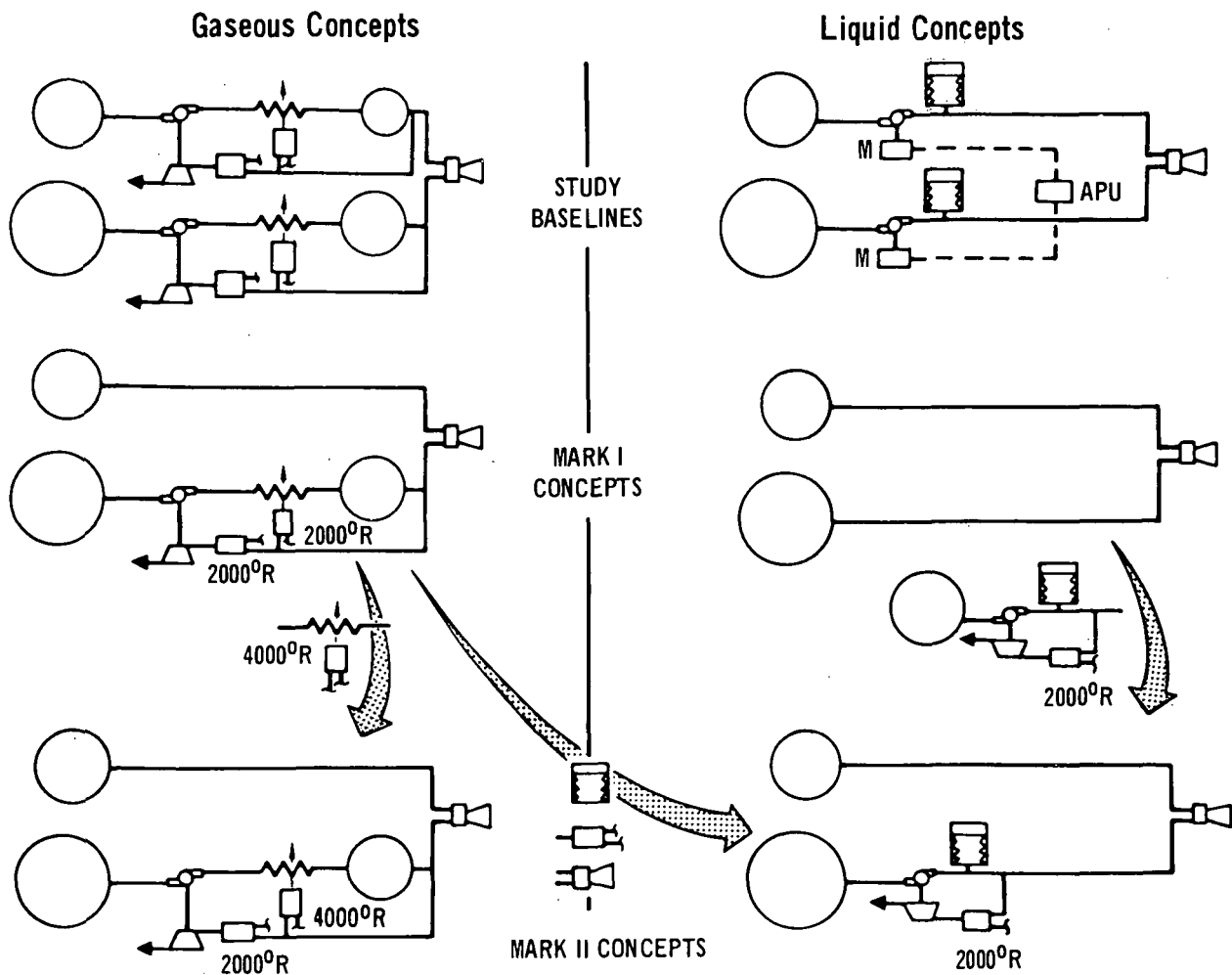


FIGURE 3-8 HYDROGEN/OXYGEN APS CONCEPT SUMMARY

#### 4. EARTH STORABLE PROPELLANT STUDIES

During the storable propellant portion of the auxiliary propulsion system study, various RCS/OMS/APU systems were considered to evaluate relative system performance, weight, complexity, flexibility, and vehicle interface characteristics. Concepts considered included various levels of RCS/OMS/APU integration. Both modular concepts and concepts installed integrally within the vehicle were evaluated. Propellant candidates were monopropellant hydrazine and hypergolic bipropellants (NTO/MMH).

The basic earth storable Reaction Control Systems are shown schematically in Figure 4-1 for both monopropellant and bipropellant configurations. During system operation,

liquid propellants are supplied at high pressure to the thrusters. Propellant tank pressures are maintained by regulated gaseous helium, and propellant acquisition is provided by surface tension screens. Component redundancy is consistent with a fail-safe, fail-safe philosophy.

The Phase C and E earth storable study was conducted for the purpose of providing design data sufficient to allow resolution of the following options:

1. Choice of propellants
2. Method of installation (modular vs integral)
3. Degree of OMS/RCS interaction
4. Degree of APU integration

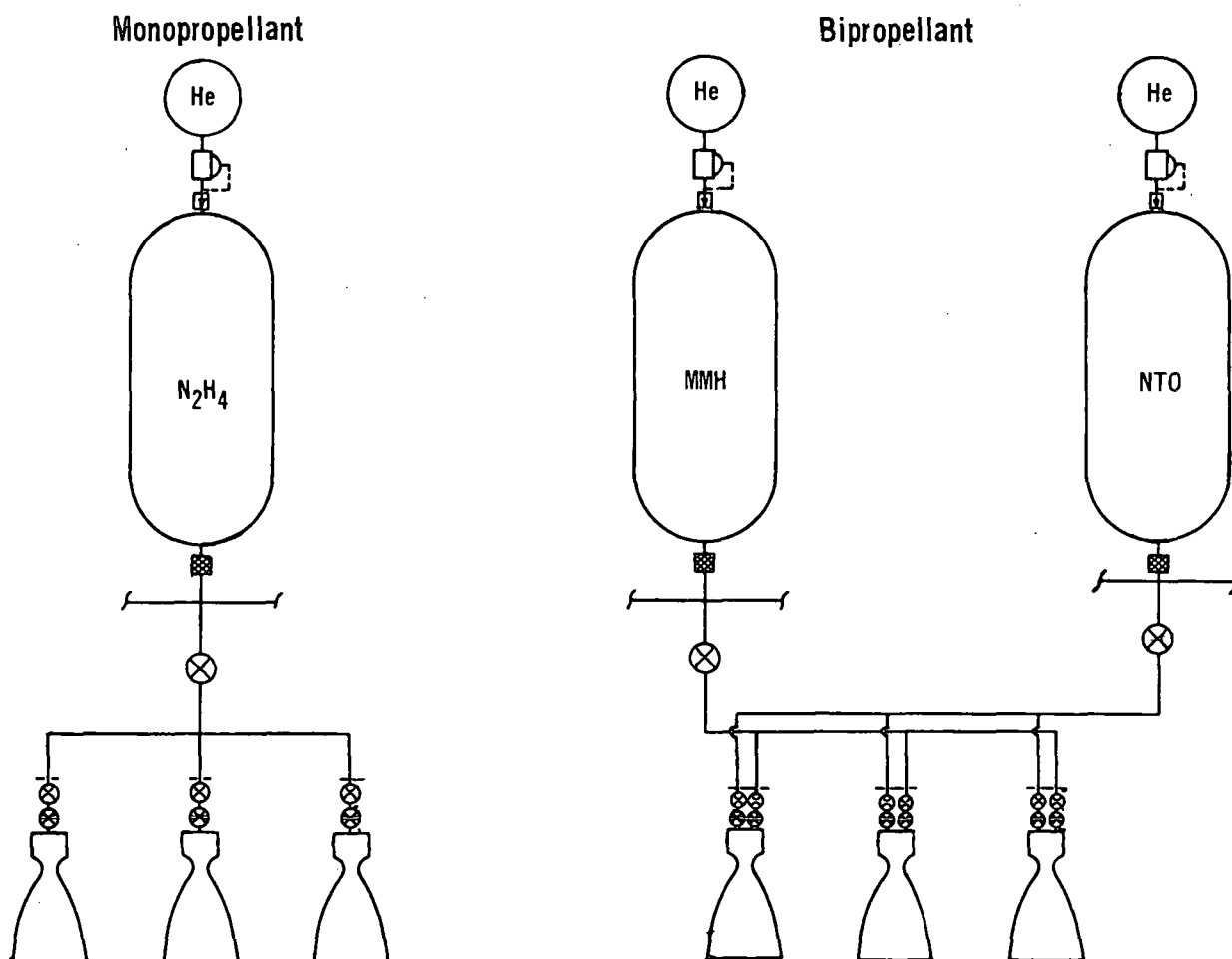


FIGURE 4-1 EARTH STORABLE RCS STUDY CONCEPTS

To fulfill these objectives, the effort was divided into two phases, RCS/OMS/APU Integration Study (Phase C), and System Performance Analysis (Phase E). The Phase C preliminary system analyses were conducted to establish nominal design points and establish system sizing data. These baseline design points then served as references for detailed design and installation studies and for concurrent studies of APU implementation, propellant utilization, and advanced pressurization and tankage concepts. In Phase E, the results from the Phase C studies and a system reuse study, conducted in parallel, were used to compare the selected concepts on the basis of safety in flight and ground operations, ease of maintenance, reusability forecasts, and complexity of flight and ground operations. Selected systems were updated and refined to incorporate installed system considerations, revisions to the component models, and revisions resulting from advanced technology studies. System analyses were then repeated to establish the design points and thus define final system weights, volumes, and component requirements.

**4.1 Requirements** - The orbiter vehicle considered in this study differed from the oxygen/hydrogen study vehicle in that it

contains no inboard main engine tankage. Instead, the main engine tanks are attached to the underside of the vehicle and are jettisoned after orbit insertion. This results in a considerably smaller orbiter than the one used in the oxygen/hydrogen studies. Figure 4-2 summarizes the changes in requirements from the O<sub>2</sub>/H<sub>2</sub> studies to the storable propellant studies. Mission requirements are common to both the O<sub>2</sub>/H<sub>2</sub> and earth storable studies and were discussed previously in Section 3.1.

Vehicle configuration studies defined three general installation arrangements, as shown in Figure 4-3. In the modular RCS concept, two wing tip pods and a nose pod house the RCS. The modular RCS(OMS) incorporates a nose pod, and two fuselage mounted side pods containing RCS thrusters which are also capable of performing OMS maneuvers. In the integral RCS concept, the tankage and thrusters are installed integrally throughout the vehicle. Impulse requirements vary for these three concepts due to differences in thruster locations. Figure 4-4 summarizes the impulse requirements for these candidate installation concepts.

**4.2 Systems Description** - Based on the Phase C preliminary studies, the six systems listed below were selected for the Phase E system performance analysis.

	O <sub>2</sub> /H <sub>2</sub> STUDIES	EARTH STORABLE STUDIES
VEHICLE	FULLY REUSABLE	PARTIALLY REUSABLE (EXPENDABLE BOOST PROPELLANT TANKS)
ORBIT INSERTION WEIGHT	330,000 LBM	265,000 LBM
SYSTEM STUDIES	RCS AND OMS	RCS, OMS, AND APU
REDUNDANCY CRITERIA	FAIL-OPERATIONAL/FAIL-SAFE	FAIL-SAFE/FAIL-SAFE
OMS OPERATION	ASCENT ABORT; ON-ORBIT ΔV TANKAGE FOR 2000 FT/SEC	ON-ORBIT ΔV TANKAGE FOR 1000 FT/SEC (ADD-ON TANKS IN PAYLOAD BAY)

FIGURE 4-2 REVISED REQUIREMENTS FOR EARTH STORABLE PROPELLANT STUDIES

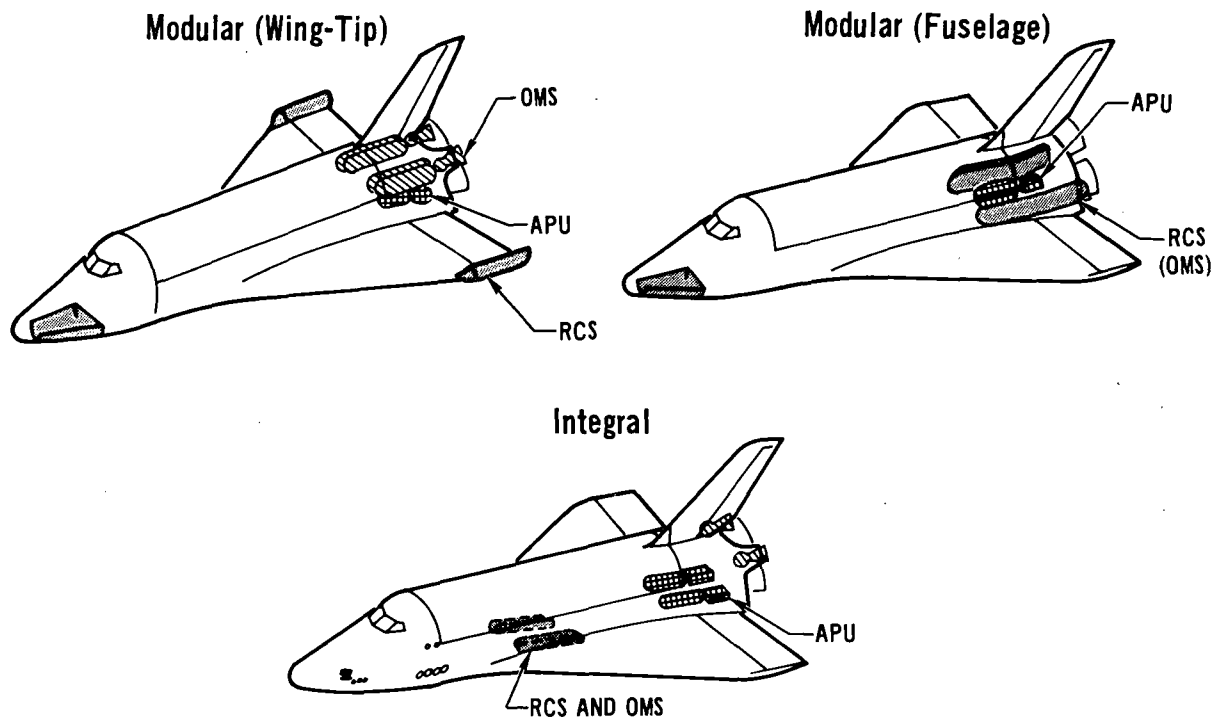


FIGURE 4-3 CANDIDATE VEHICLE INSTALLATIONS

	IMPULSE REQUIREMENT, LB-SEC				
	INTEGRAL RCS	MODULAR RCS		MODULAR RCS (OMS)	
		NOSE POD	EACH WING POD	NOSE POD	EACH FUSELAGE POD
ON-ORBIT TRANSLATIONS	1,133,470	136,995	498,845	119,500	4,449,674 (OMS = 3,915,924) (RCS = 533,750)
ATTITUDE MANEUVERS	167,321	26,320	64,225	69,000	52,250
ON-ORBIT LIMIT CYCLE	35,315	6,420	24,830	20,575	15,222
RCS DISTURBANCE	48,260	21,445	26,540	25,675	30,470
REENTRY - YAW	333,712	302,330		302,330	
- ROLL	123,000		14,430		47,000
- PITCH	58,600		40,280		39,500
		493,510	669,150	537,080	4,634,116
TOTAL	1,899,678	1,831,810		9,805,313	

FIGURE 4-4 IMPULSE REQUIREMENTS

1. Modularized monopropellant RCS
2. Modularized bipropellant RCS
3. Modularized bipropellant RCS performing all maneuvers
4. Integral bipropellant RCS sharing common tankage with the OMS
5. Integral monopropellant RCS sharing common tankage with the APU
6. Modularized monopropellant APU

**Modularized Monopropellant RCS** - The installation of this concept is illustrated in Figure 4-5. In this baseline design, the two wing tip pods and nose pod are used for all on-orbit RCS functions. Reentry yaw is provided entirely by the nose pod. The forward-firing thrusters of the wing tip pods are

protected against the high reentry heating rates and heat loads by thermal protection doors. As shown, the doors and door hydraulic actuation mechanisms are attached to the wing, thus facilitating pod installation and removal by eliminating the need for a hydraulic interface between the pod and wing.

**Modularized Bipropellant RCS** - The basic installation features of the monopropellant and bipropellant modular RCS differ very little. A typical bipropellant nose pod installation is shown in Figure 4-6. The thrusters in the nose pod are canted to provide, in conjunction with the wing tip thrusters, up-down and left-right translational maneuvers. A separate fuselage mounted OMS is used to perform high ( $\geq 20$  ft/sec)  $\Delta V$  maneuvers.

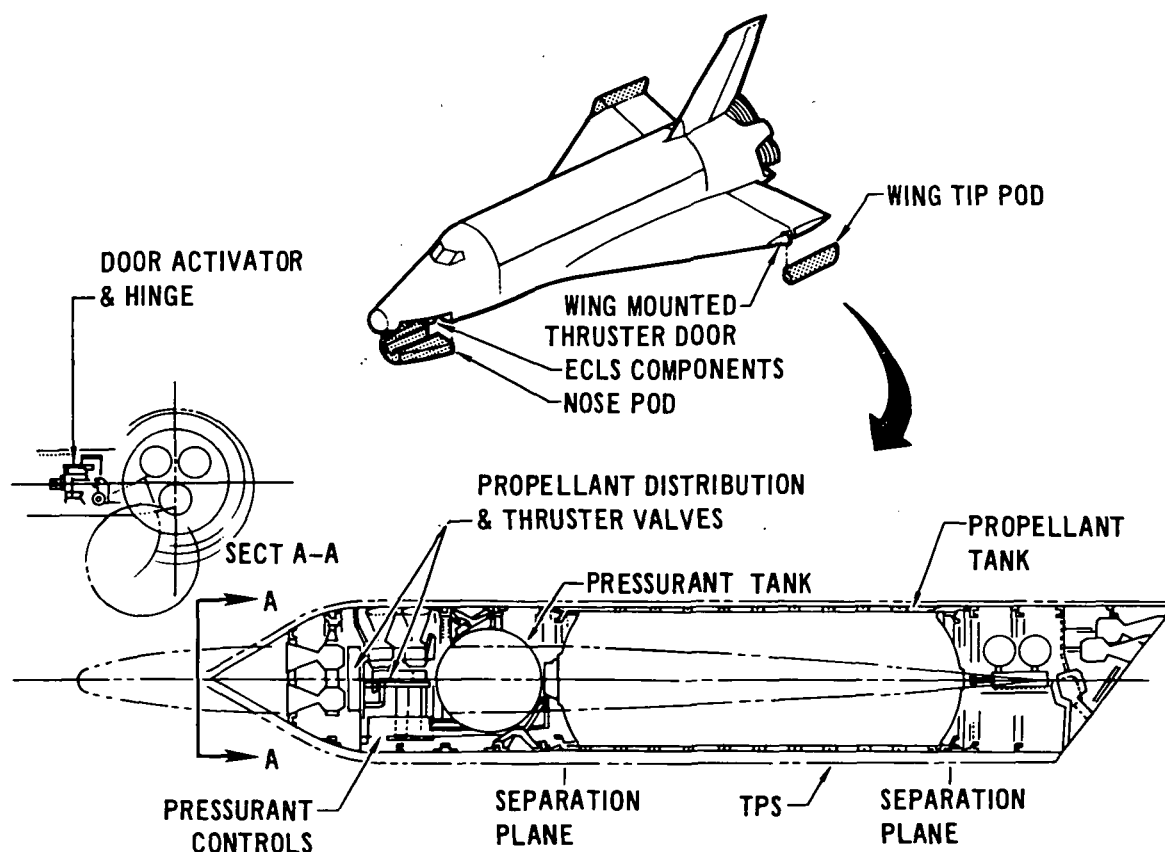


FIGURE 4-5 WING TIP RCS POD INSTALLATION

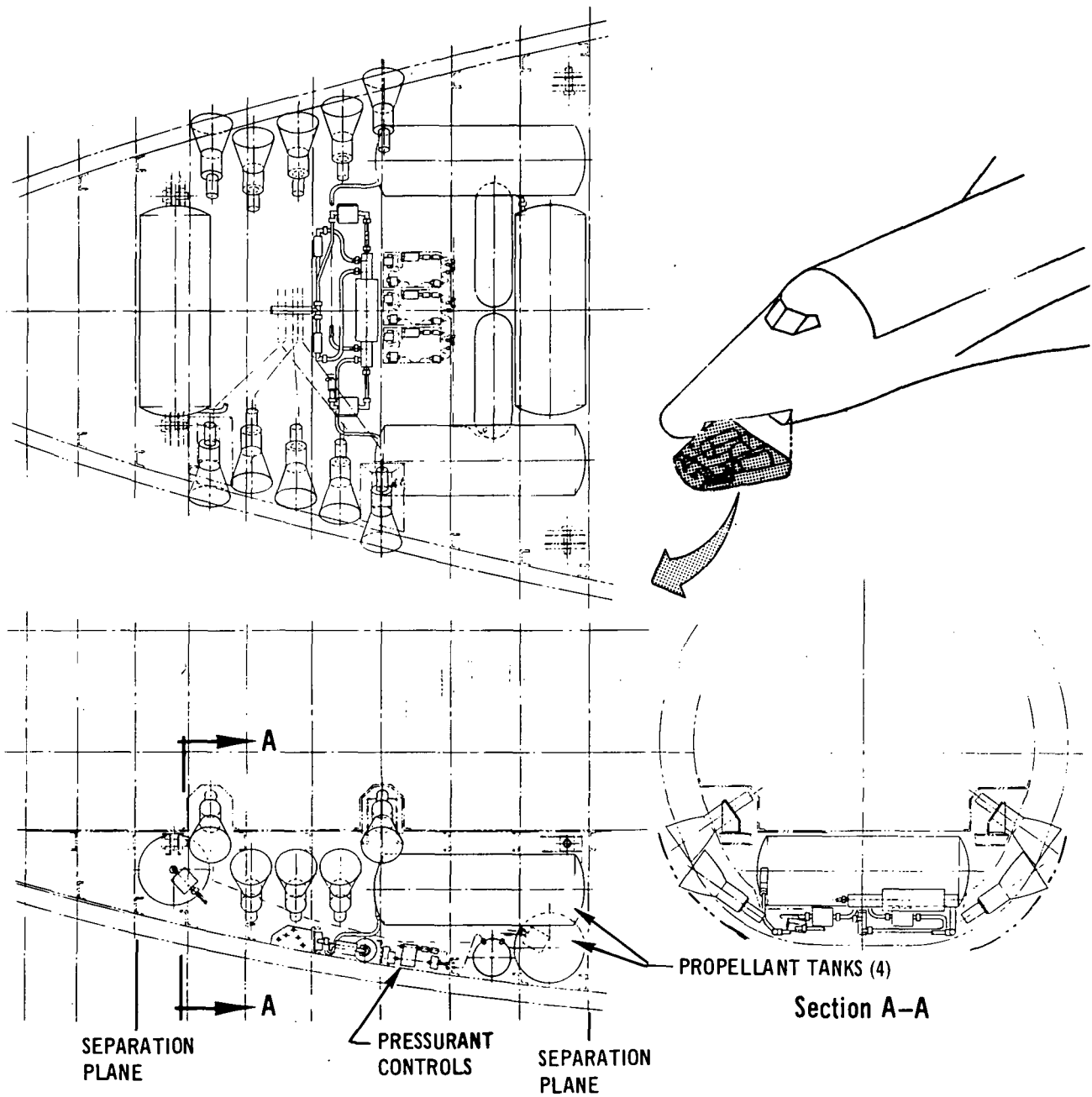


FIGURE 4-6 NOSE RCS POD INSTALLATION



Modularized Bipropellant RCS(OMS) - Figure 4-7 illustrates the general arrangement and pod installation of the Modular RCS(OMS) configuration. In this concept, forty-eight RCS thrusters are used to perform all maneuvers, thereby eliminating the need for a dedicated OMS engine. The nose pod arrangement for this design is similar to the nose installation for the modular RCS case (Figure 4-6). One of the principle design features of the fuselage-mounted side pods is that they are shielded by the wings during reentry. The pod location and shape are tailored to preclude any interference with the payload bay door. Landing center-of-gravity problems are minimized in the Modular RCS(OMS) by extending the side pods forward of the aft payload bulkhead and by

placing the oxidizer tanks in the most forward portions of the pods.

Integrated Bipropellant RCS/OMS - Figure 4-8 depicts the installation of the integrated RCS/OMS. As illustrated, the entire system is installed integrally within the vehicle. The design incorporates thirty-seven 600 lbf RCS engines and two 6000 lbf OMS engines which are served by common tankage. The two fuel and two oxidizer tanks are mounted directly below the payload bay to minimize axial center-of-gravity changes and to preclude the need for a propellant dump during launch aborts. Vertical center-of-gravity travel is accommodated by gimballing the OMS engines.

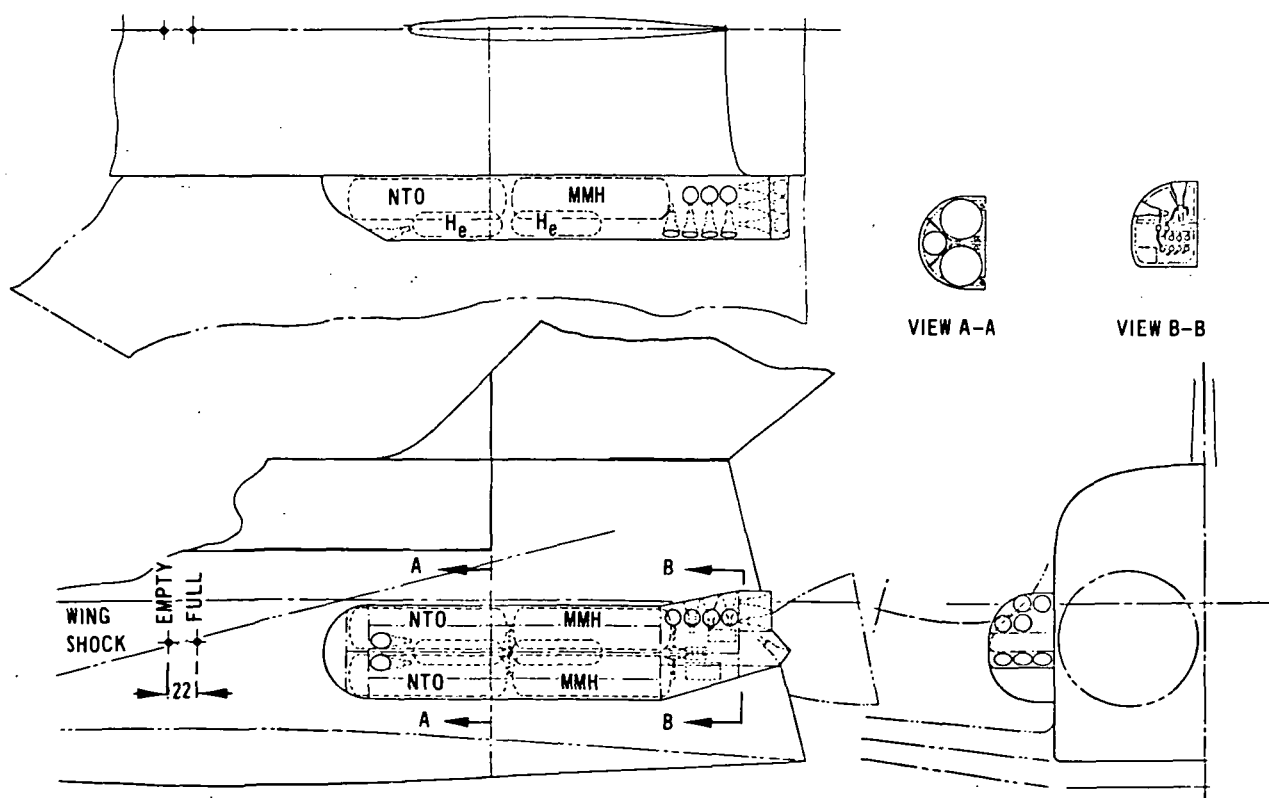


FIGURE 4-7 MODULARIZED RCS (OMS) SIDE PODS

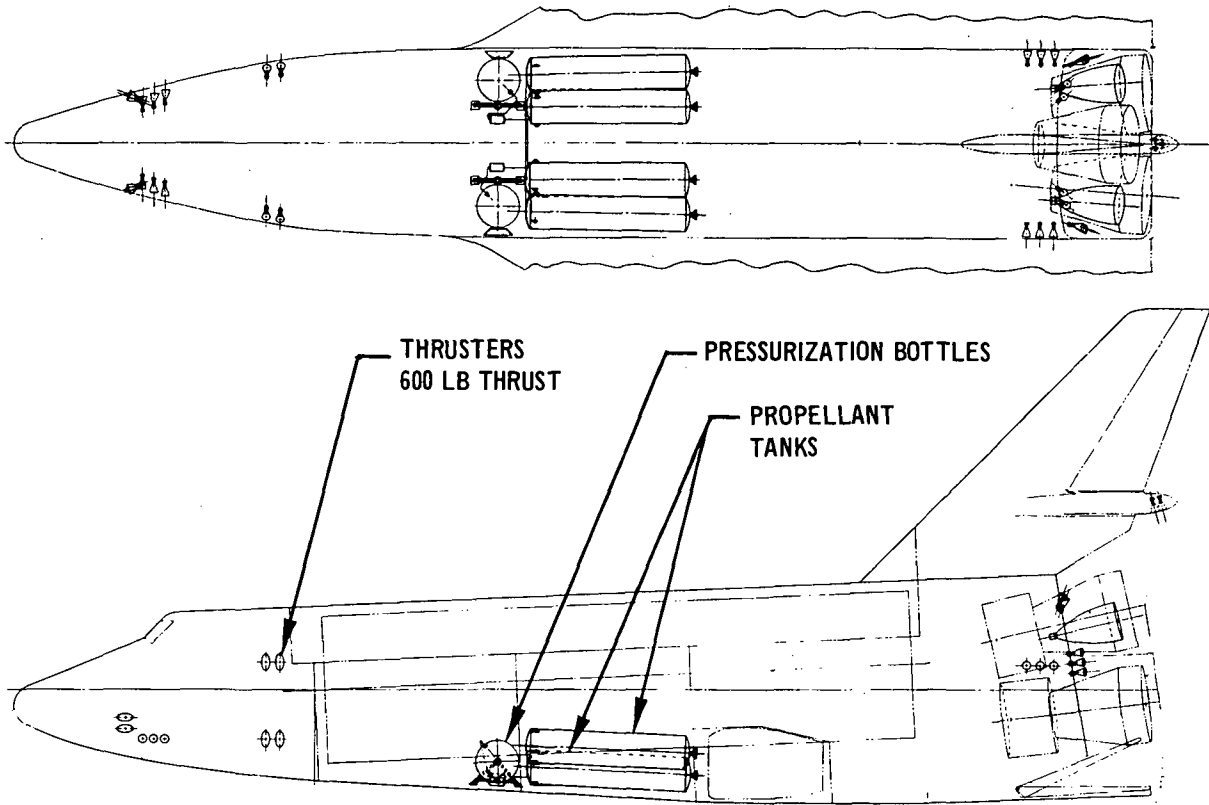


FIGURE 4-8 INTEGRATED RCS AND OMS INSTALLATION

Modular Monopropellant APU and Integrated Monopropellant RCS/APU - The APU is installed modularly within the rear fuselage. The design incorporates two monopropellant tanks and four APU's. In normal operation, two of the APU's are active, one is idle, and one dormant. In the integrated RCS/APU concept, the propellant is supplied to the APU's and RCS thrusters from common tankage installed integrally below the payload bay. APU propellant pressure is raised in this case from tank pressure to a higher chamber pressure by an APU-driven boost pump.

**4.3 Design Definition** - The schematic for the modular bipropellant RCS and modular bipropellant RCS(OMS), shown in Figure 4-9, is typical of all candidate concepts. Propellant tank operating pressure is maintained by the

use of pressure regulators, and regulation redundancy is provided by utilizing three parallel regulator branches. Equality in propellant tank pressures (bipropellant systems) is effected by the pressure equalizing valve located downstream of the oxidizer helium regulator. On-orbit propellant acquisition is accomplished by cylindrical surface tension screens. Because reentry accelerations will cause screen breakdown, a false bottom is incorporated in the tanks to isolate sufficient propellant in the lower compartment for entry maneuvers. Thrusters are grouped in sets of two or three, and in the event of a malfunction, can be isolated either individually or in groups. Upon completion of the mission, a helium purge downstream of the thruster isolation valves is accomplished using residual pressurant.

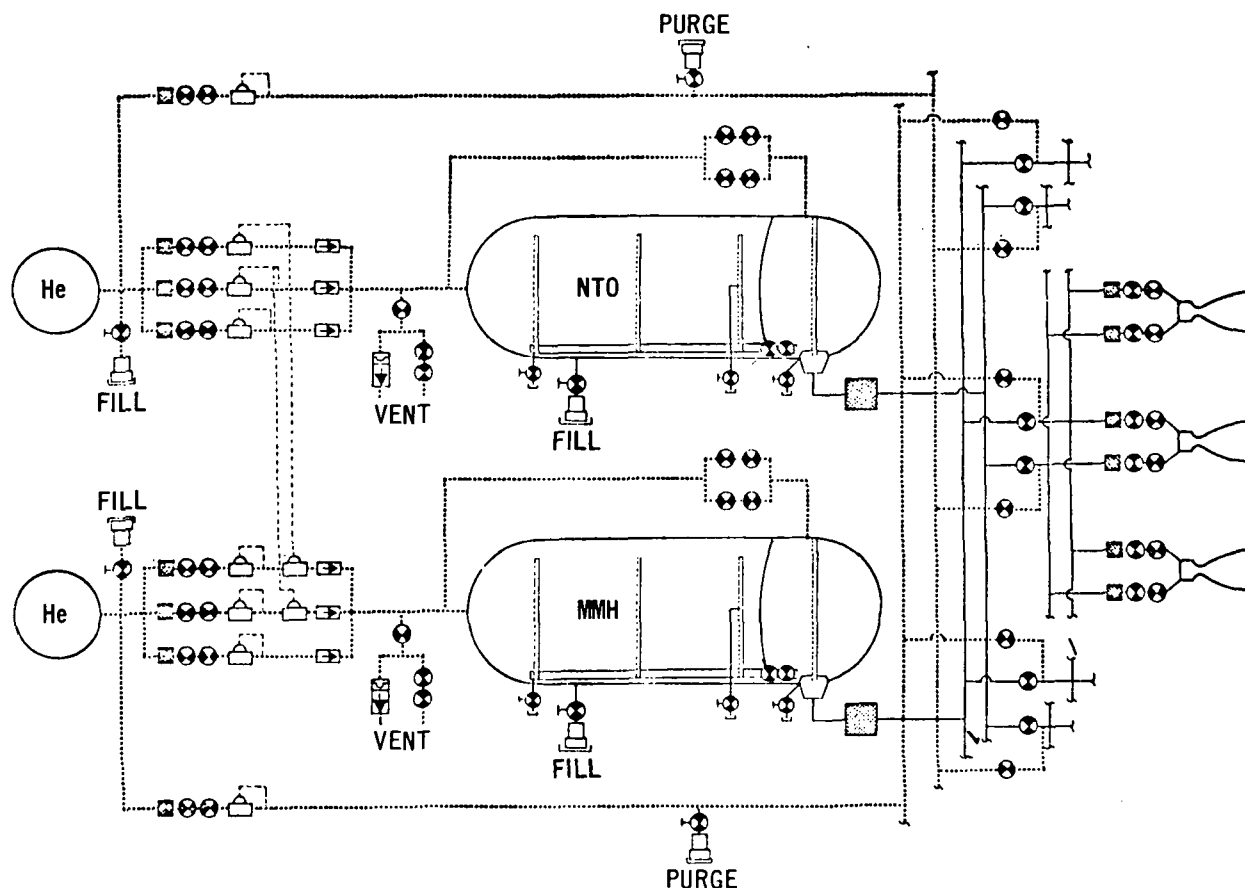


FIGURE 4-9 MODULAR RCS - NTO/MMH  
MODULAR RCS (OMS) - NTO/MMH

Figure 4-10 summarizes the design conditions for the six candidate Phase E configurations. These design configurations have evolved based on the preliminary (Phase C) studies and the alternate configuration analyses. The following paragraphs provide a summary of the alternate design approaches considered for the thrusters, tankage, pressurization, and thermal control. Also provided is a description of the designs selected, their operation, and the analysis and rationale determining their selection.

**4.3.1 Thruster Assemblies** - The analytical model for the monopropellant thruster was defined by the Aerojet Liquid Rocket

Company (ALRC). A schematic drawing of the monopropellant thruster assembly with the associated pressure budget, performance, and weights is shown in Figure 4-11. Design thrust is 600 lbf at a chamber pressure of 150 lbf/in<sup>2</sup>. The injector, fabricated from 304L stainless steel, supplies fuel to the catalyst bed at low velocities. The Shell 405 catalyst granules are retained by two layers of screen and a cylindrical, perforated tube retainer. The catalyst is contained within a compartment which provides lateral and columnar support to the catalyst granules. All parts of the catalyst compartment and nozzle are fabricated from Hastelloy B.

MODULAR RCS	- $N_2H_4$	WING AND NOSE MODULES UTILIZING HELIUM PRESSURIZATION; TITANIUM TANKAGE; SURFACE TENSION PROPELLANT EXPULSION; CONVENTIONAL NOZZLE THRUSTERS; ELECTRIC HEATER/HEAT PIPE THERMAL CONTROL; NO PROPELLANT INTERCONNECTS BETWEEN MODULES
	- NTO/MMH	WING AND NOSE MODULES CONTAINING HELIUM PRESSURIZATION; ULLAGE PRESSURE EQUALIZATION; TITANIUM TANKAGE; SURFACE TENSION PROPELLANT EXPULSION; FILM-COOLED THRUSTERS; ELECTRIC HEATER THERMAL CONTROL; NO INTRA-MODULE INTERCONNECTS
MODULAR RCS (OMS)	- NTO/MMH	BIPROPELLANT FUSELAGE AND NOSE MODULES CONTAINING HELIUM PRESSURIZATION; ULLAGE PRESSURE EQUALIZATION; TITANIUM TANKAGE; SURFACE TENSION PROPELLANT EXPULSION; FILM-COOLED THRUSTERS; ELECTRIC HEATER THERMAL CONTROL; NO INTRA-MODULE INTERCONNECTS
INTEGRATED RCS/OMS	- NTO/MMH	BIPROPELLANT SYSTEM WITH COMMON, INTEGRATED TANKAGE; HELIUM PRESSURIZATION; ULLAGE PRESSURE EQUALIZATION; TITANIUM TANKS; SURFACE TENSION PROPELLANT EXPULSION; FILM-COOLED RCS THRUSTERS; REGEN-COOLED OMS ENGINES (2); ELECTRIC HEATER THERMAL CONTROL
INTEGRATED RCS/APU	- $N_2H_4$	MONOPROPELLANT SYSTEM WITH COMMON, INTEGRATED, TITANIUM TANKAGE; HELIUM PRESSURIZATION/APU BOOST PUMP; SURFACE TENSION PROPELLANT EXPULSION; CONVENTIONAL NOZZLE THRUSTERS; WATER-COOLED APU; ELECTRIC HEATER/HEAT PIPE THRUSTER THERMAL CONTROL
MODULAR APU	- $N_2H_4$	MONOPROPELLANT SYSTEM WITH ACTIVE-ACTIVE-IDLE-DORMANT REDUNDANCY; MANIFOLDED TITANIUM TANKAGE; HELIUM PRESSURIZATION; SURFACE TENSION PROPELLANT EXPULSION; THERMAL BED GAS GENERATOR; MODULATED, WATER-COOLED HYDRAULIC SYSTEM, CONDUCTIVE-COOLED ALTERNATORS

FIGURE 4-10 PHASE E SYSTEM STUDIES

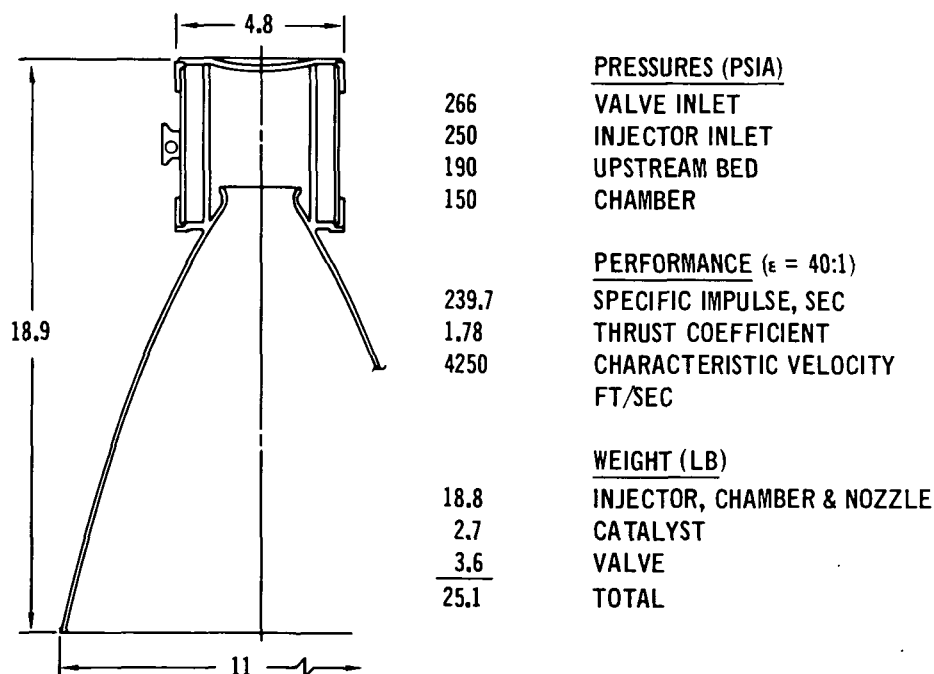


FIGURE 4-11 600 LBF MONOPROPELLANT THRUSTER ASSEMBLY

It is estimated that monopropellant thruster catalyst beds will require replacement every 5 to 10 flights. Due to this anticipated high repair frequency, interest has been focused on monopropellant thruster maintenance. In the thruster installation concept depicted in Figure 4-12, the thruster and thruster valve are separately mounted to support structure; gland seals between the two components permit the thruster to be removed without disturbing the valve(s) or necessitating system drain and decontamination. The series thruster valves adequately protect ground personnel from the toxic propellant. Once removed, the entire unit would be transferred to the supplying facility for servicing. Catalyst pack replacement would

be accomplished by cutting open the thrust chamber body, replacing the bed, and rewelding the chamber. Flight acceptance tests would be performed at the same facility.

The bipropellant thruster model employed in this study was fuel film cooled, and consisted of a stainless steel parallel platelet injector and an integral thrust chamber and nozzle of silicide coated columbium. Figure 4-13 presents the thruster performance sensitivities.

Two methods of maximizing the RCS(OMS) thruster performance have been implemented in this analysis:

1. Use of statistically determined higher performance thrusters for the -X function.
2. Reduced thruster film cooling.

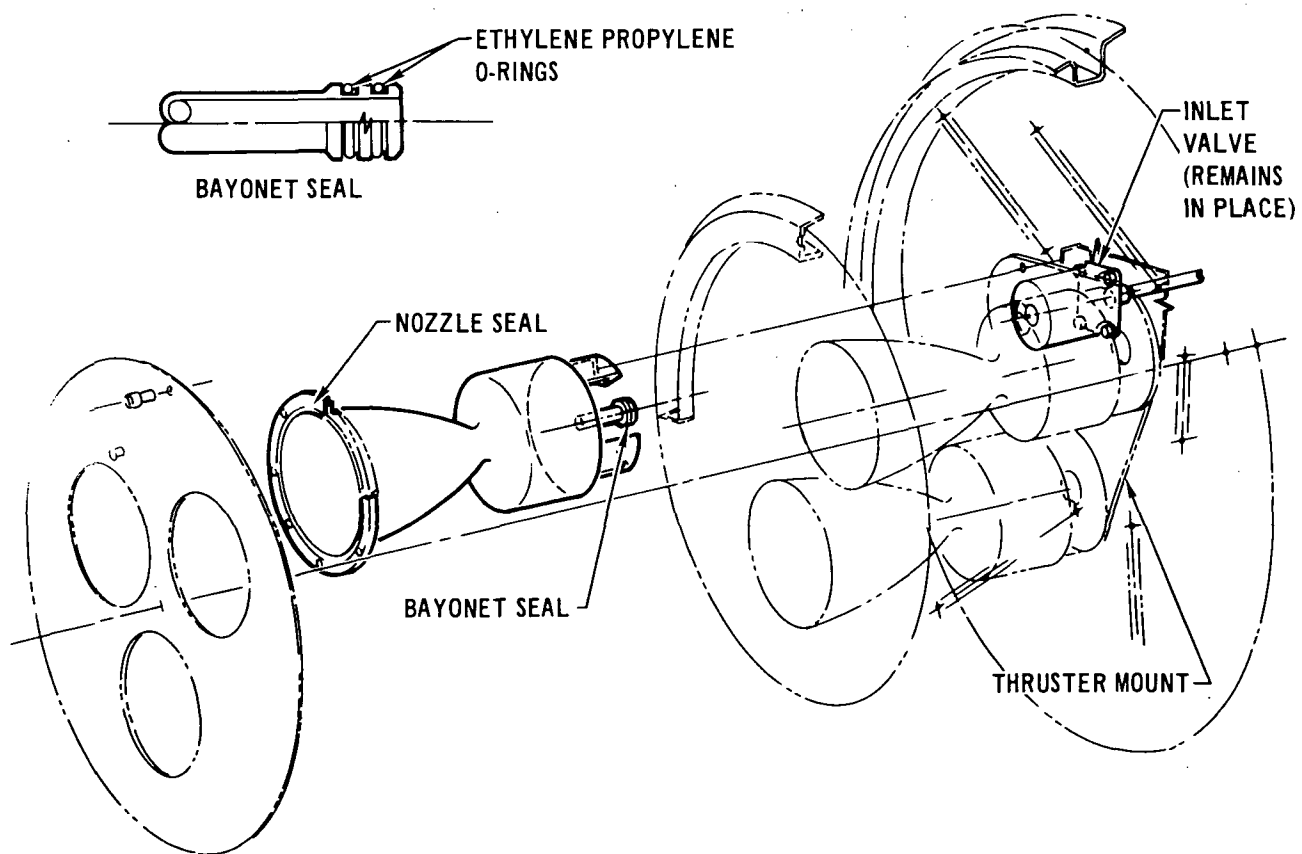


FIGURE 4-12 MONOPROPELLANT THRUSTER INSTALLATION

DESIGN POINT	WEIGHT BREAKDOWN - LBM	PRESSURE BUDGET - LBF/IN. <sup>2</sup>
F = 600 LBF	INJECTOR 3.6	VALVE INLET 300
P <sub>C</sub> = 200 PSIA	CHAMBER AND NOZZLE 3.5	INJECTOR INLET 270
ε = 40:1	VALVE 4.4	CHAMBER 200
MR = 1.65	11.5	

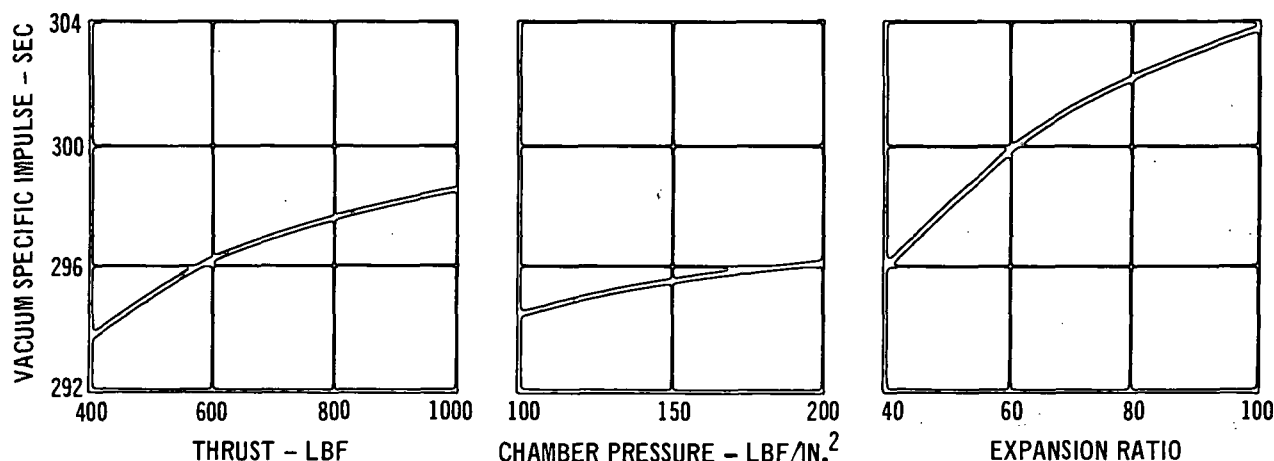


FIGURE 4-13 BIPROPELLANT RCS THRUSTER PERFORMANCE

Although RCS weight is relatively insensitive to RCS performance (21 lbm / sec specific impulse), improvements in the -X translational performance result in significant weight savings (103 lbm/sec). To take advantage of this potential weight savings, a statistical procedure for selecting high performance thrusters is proposed. In this method, illustrated in Figure 4-14, thruster performance data from injector tests and/or thruster flight acceptance tests is used to identify the higher performing injectors. The average increase in selected thruster performance relative to the shipset nominal value is dependent upon the ratio of the number of -X thrusters required to the number of thrusters per shipset. For the RCS(OMS), where 12 out of 48 thrusters are required, the average performance gain is three seconds. Concurrent with the -X thruster performance gain is a one second performance degradation in the remaining 36 thrusters of the shipset.

The second method of improving thruster performance is to design for a shorter service life. The data presented in Figure 4-13 is

based on a nominal wall temperature of 2200°F, and corresponds to 22% fuel film cooling. Since the primary life constraint is the number of thruster cold starts, thruster replacement rates are established by the RCS thrusters. 2200°F is consistent with a 100 mission life. A decrease in the percent film cooling sufficient to yield a one second performance gain results in a thruster replacement every 50 missions.

The implementation of these two modifications on the modular RCS(OMS) thruster results in a -X translational thruster specific impulse of 306.2, or four seconds greater than the nominal performance. This value was used for the RCS(OMS) sizing analysis.

**4.3.2 Tankage and Propellant Acquisition Assembly** - The baseline propellant storage concept for this study consisted of 6A1-4V Titanium tankage with a surface tension acquisition device. This design was the result of an evaluation of candidate expulsion devices and a review of materials compatibility.

APPROACH: THRUSTER PERFORMANCE DATA FROM INJECTOR TESTS AND/OR THRUSTER FLIGHT ACCEPTANCE TESTS WILL BE USED TO SCREEN HIGH-PERFORMANCE THRUSTER S/N'S FOR THE AXIAL TRANSLATION FUNCTIONS

MARQUARDT R4D PERFORMANCE DISTRIBUTION  
434 THRUSTER SAMPLES

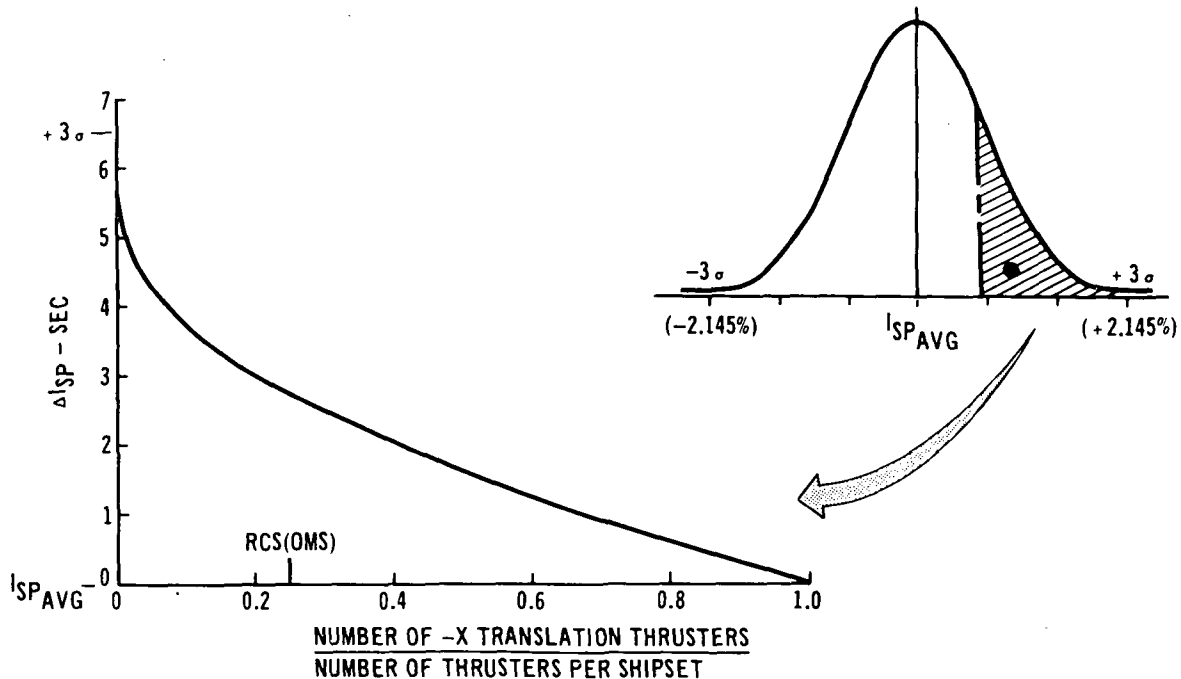


FIGURE 4-14 PERFORMANCE SCREENING OF RCS (OMS) THRUSTERS

Shuttle reusability requirements have limited consideration of propellant acquisition concepts to nonmetallic bladders/diaphragms, metallic bellows, pistons and surface tension positive expulsion devices. Figure 4-15 summarizes the relative merits of these concepts.

Surface tension devices were chosen as the baseline propellant acquisition method for this study. Devices of this type are passive, thus providing high reliability and unlimited reuse capability. The design consists of screen channels located around the tank circumference, plus a single enclosed collector manifold which connects each channel to the outlet sump.

The acquisition device will selectively pass liquid to the feed system as long as there is contact with the liquid mass. The wall oriented nature of the device ensures that this contact will be made. Screen mesh and flow passage dimensions are selected so that the

pressure drop across the screen vapor/liquid interface never exceeds the screen bubble point prior to reentry. During reentry, deceleration forces result in channel draining; however, these same forces will orient the propellant at the outlet of the tank for continued propellant use.

**4.3.3 Pressurization Assembly** - A regulated ambient temperature storage helium pressurization system served as the reference for this study. This system employs gaseous helium stored at 4500 lbf/in.<sup>2</sup> in titanium pressure bottles. For bipropellant systems, the fuel and oxidizer have separate pressurization systems to preclude the possibility of propellant vapor mixing and reaction within the pressurization system. Propellant tank operating pressure is maintained by the use of pressure regulators, and redundancy is provided with three parallel regulator branches.

	BLADDER/DIAPHRAGM	METALLIC BELLOWS	PISTON	SURFACE TENSION
CYCLE LIFE	150 (ELASTOMER) 15-30 (TEFLON)	500	1000	UNLIMITED
RELATIVE WEIGHT	1.0	3.0	2.7	1.3
PERMEATION/LEAKAGE	HIGH PERMEATION	NEGLECTIBLE	LIQUID FILM ON WALL FOLLOWING EXPULSION	SATURATED PROPELLANTS
SENSITIVITY TO DYNAMIC ENVIRONMENT	SUSCEPTIBLE TO TEARS AND CLAMP-UP FAILURES DURING SLOSH	PRONE TO CONVOLUTION WEAR AND IMPACT DAMAGE	PISTON COCKING	CHANGE IN EFFECTIVE PORE SIZE
DEVELOPMENT STATUS	GOOD	GOOD	FAIR	GOOD → FAIR; SMALL TANKS OR SUMPS FAIR → POOR; LARGE TANKS
DEVELOPMENT RISK	LOWEST RISK AND COST	MODERATE: QUESTIONABLE AVAILABILITY OF LARGE DIAMETER, SEAMLESS TUBING	MODERATE: MAJOR DEVELOPMENT EFFORT ASSOCIATED WITH BACK- UP ROLLING DIAPHRAGM	MODERATE TO HIGH: UNABLE TO GROUND TEST LARGE TANKS
MAJOR ADVANTAGES	SIMPLE, LIGHTWEIGHT DEVICE	POSITIVE SEPARATION OF PROPELLANT AND PRES- SURANT; CONTROL OF FAILURE MODE BY SELEC- TION OF CORE SPRING CONSTANT; GOOD PROPEL- LANT STORABILITY	SIMPLE DEVICE WITH GOOD CYCLE LIFE	PASSIVE DEVICE WITH POTENTIAL FOR UNLIMITED LIFE
MAJOR DISADVANTAGES	POOR CYCLE LIFE; PERMEABLE MATERIALS; BLADDER ADSORBS PROPELLANT	HEAVY AND DIFFICULT TO CLEAN (CORROSION)	RESIDUAL LIQUID FILM; EXPOSURE OF DYNAMIC SEALS TO PROPELLANTS	DIFFICULT TO TEST AND TO VERIFY INTEGRITY; DUTY CYCLE SENSITIVE

FIGURE 4-15 SUMMARY OF CANDIDATE EXPULSION DEVICES

In depth studies were conducted to evaluate the weight savings potential offered by advanced pressurization concepts. Pump fed, volatile liquid, and hydrazine decomposition (monopropellant systems only) pressurization systems were compared to the reference regulated helium system from the viewpoints of weight and complexity. The alternate systems are shown conceptually in Figure 4-16.

A comparison of the primary considerations for the four concepts is presented in Figure 4-17. The significant conclusions drawn from these comparisons are:

1. For monopropellant systems, hydrazine

decomposition pressurization does show a weight savings over a regulated helium system but at the expense of increased complexity.

2. A pump feed system is lighter than its regulated helium counterpart, again with increased system complexity. Additionally, this system requires liquid pressure regulators, when used in bipropellant systems; to avoid large mixture ratio excursions.
3. Volatile liquid pressurization, although attractive from a reusable-refillable module aspect, is not weight competitive with any of the other systems.



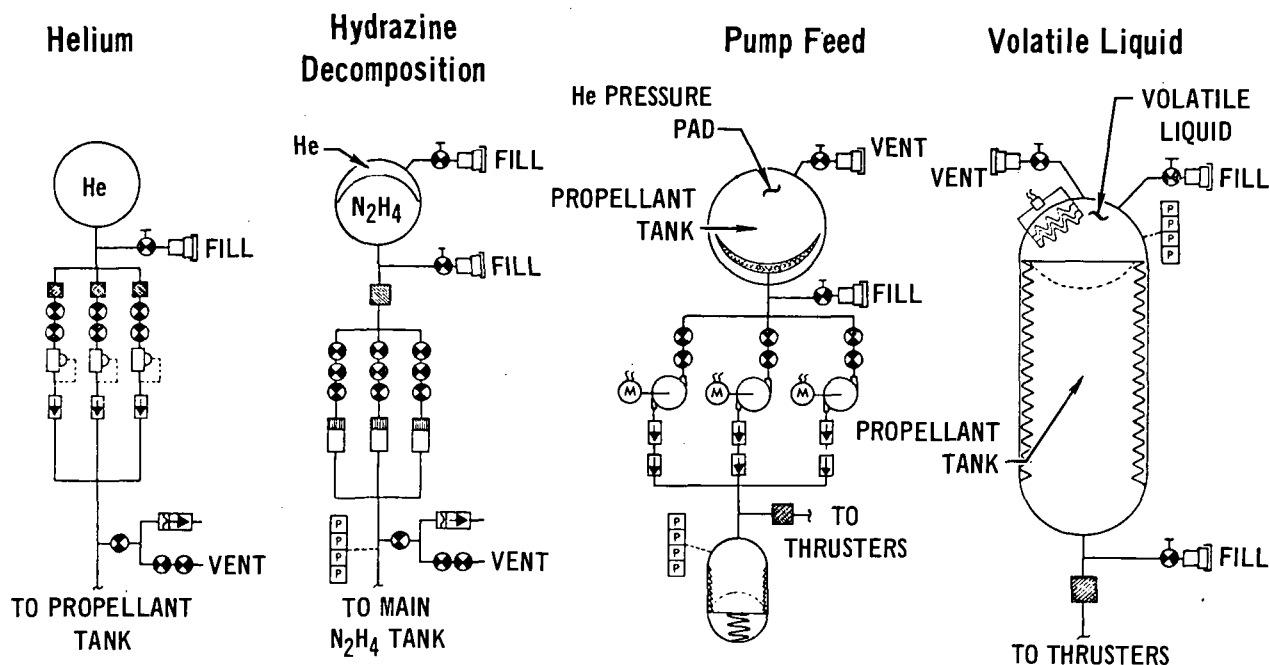


FIGURE 4-16 ALTERNATE PRESSURIZATION CONCEPTS

	REGULATED HELIUM	N <sub>2</sub> H <sub>4</sub> DECOMPOSITION	PUMP FEED	VOLATILE LIQUID
RELATIVE WEIGHT				
- APU	+ 137	+ 20	REF	+ 43
- MONOPROPELLANT RCS	+ 375	REF	+ 100	+ 1075
- BI-PROPELLANT RCS (OMS)	+ 700	-	REF	+ 4400
RELATIVE VOLUME	5.0	1.0	2.0	2.2
PRESSURE BAND	+ 2.5%	+ 2.7%	+ 100% - 0%	+ 85% - 0%
DESIGN OPERATING TEMPERATURE	AMBIENT	200°F	AMBIENT	125 - 165°F
SENSITIVITY TO MISSION DUTY CYCLE	FAIRLY INSENSITIVE	FAIRLY INSENSITIVE	ACCUMULATOR SIZE LIMITS RCS ΔV	HEATER POWER LEVEL LIMITS TOTAL RCS THRUST
PROPELLANT UTILIZATION UNBALANCE ERROR CONTROL BUDGET	SMALL	SMALL	LARGE Q/F ERROR FOR ACCUMULATORS OUT-OF-PHASE	LARGE ERRORS DUE TO MODULE TEMPERATURE DIFFERENCES
MAJOR ADVANTAGES	WIDE APPLICATION: MINIMAL DEVELOPMENT	LIGHTWEIGHT: REDUCES THERMAL CONTROL	LIGHTWEIGHT: PRESURANT LEAKAGE NOT CRITICAL	RELIABLE-NO-MOVING PARTS. NO FILL VENT REQUIREMENT FOR RECYCLE
MAJOR DISADVANTAGES	HEAVY: HIGH REGULATOR FAILURE RATE	COMPLEX: TIGHT PRESSURE DEADBAND NECESSITATES MANY PUMP CYCLES: REQUIRES HEAT EXCHANGER	WIDE VARIATION IN THRUSTER INLET PRESSURE OR HIGH PUMP POWER:	HEAVY: WIDE PRESSURE BAND: HIGH POWER REQUIREMENT

\*WITHOUT LIQUID PRESSURE REGULATION

FIGURE 4-17 COMPARISON OF CANDIDATE PRESSURIZATION CONCEPTS

**4.3.4 Thermal Control** - Analysis was performed to evaluate the technical complexity and to define the weight implications associated with the thermal control of the alternate RCS configurations. Module thermal control is required primarily to protect the system from the extreme environments in space, as well as those induced during entry. Additionally, monopropellant thruster injectors require cooling to preclude explosive decomposition of the propellant under certain malfunction conditions. The primary thermal constraints are associated with the propellants and the thrusters. Allowable propellant temperature ranges have been established to be 40 to 125°F for bipropellants (NTO/MMH) and 50 to 125°F for monopropellant hydrazine. The steady state and transient thermal response of the wing tip RCS modules have been examined using a two-dimensional thermal model. These calculations indicate that the maximum steady state uncontrolled temperature range is -110 to 165°F. Minimum temperatures, which occur with continuously shaded pods, require heaters to prevent propellant freezing. Heaters are sized to provide a maximum power of 303 watts for the monopropellant system (including 10 watts per thruster to maintain a minimum 150°F catalyst temperature), and 161 watts for a bipropellant system. Corresponding maximum energy requirements are 36.8 kwh (monopropellant system) and 17.3 kwh (bipropellant system). The maximum temperature of 165°F is somewhat above the desired maximum temperature, and thermal control is required to prevent propellant overheating.

Thruster thermal requirements have been defined in order to provide adequate thruster life and reliability. Figure 4-18 summarizes the thermal limitations associated with monopropellant thruster start up, operation, heat soakback, and nonoperation. The counteracting constraints on minimum catalyst bed temperature and maximum injector soakback temperature are of primary significance. The restriction on minimum catalyst temperature arises from the poor structural properties of the spontaneous catalyst (Shell 405) and its tendency to

generate "fines" under repeated cold thruster starts. The restriction on injector temperature is based on propellant thermal stability considerations, i.e., the maximum injector temperature is kept sufficiently low so as to preclude explosive detonation of the propellant under certain malfunction conditions.

Thermal control of bipropellant thrusters is not as restrictive. The primary concern for bipropellant thrusters is with vacuum-ignition pressure spiking. During pulsing operation, energy-rich detonatable chemical residues (mostly monomethylhydrazine nitrate) can accumulate and, in sufficient quantity, can produce high-magnitude ignition overpressures. To alleviate this problem on the Apollo CSM and LM RCS, the thruster injectors were maintained in excess of 70°F to promote rapid vaporization of the fuel. Meeting this same criteria with 600 lbf thrusters will require a maximum power input of 5.4 watts/thruster.

The basic aspect of monopropellant thruster thermal control is the conduction path between the thruster and the surrounding structure. To minimize the injector and valve seat temperature, it would be desirable to attach the injector and valve to massive structure with a high heat capacity. However, such a connection would provide a substantial heat short during periods of nonoperation, and would thus conflict with the goal of minimizing the heater power required to maintain minimum catalyst temperature. Of the alternate thermal connection concepts which were evaluated, the most attractive was a heat pipe.

In order to determine the operational considerations of a heat pipe system, a thermal model of the module was constructed. This model was used to determine the steady state heater requirements necessary to maintain thruster minimum temperatures, to determine the heat delivered to the Environmental Control and Life Support (ECLS) during thruster soakback, and the system transient response. The thruster-ECLS model was used to examine the response of the thruster, the mounting plate, and the module during a heat soakback condition. For the single firing case,

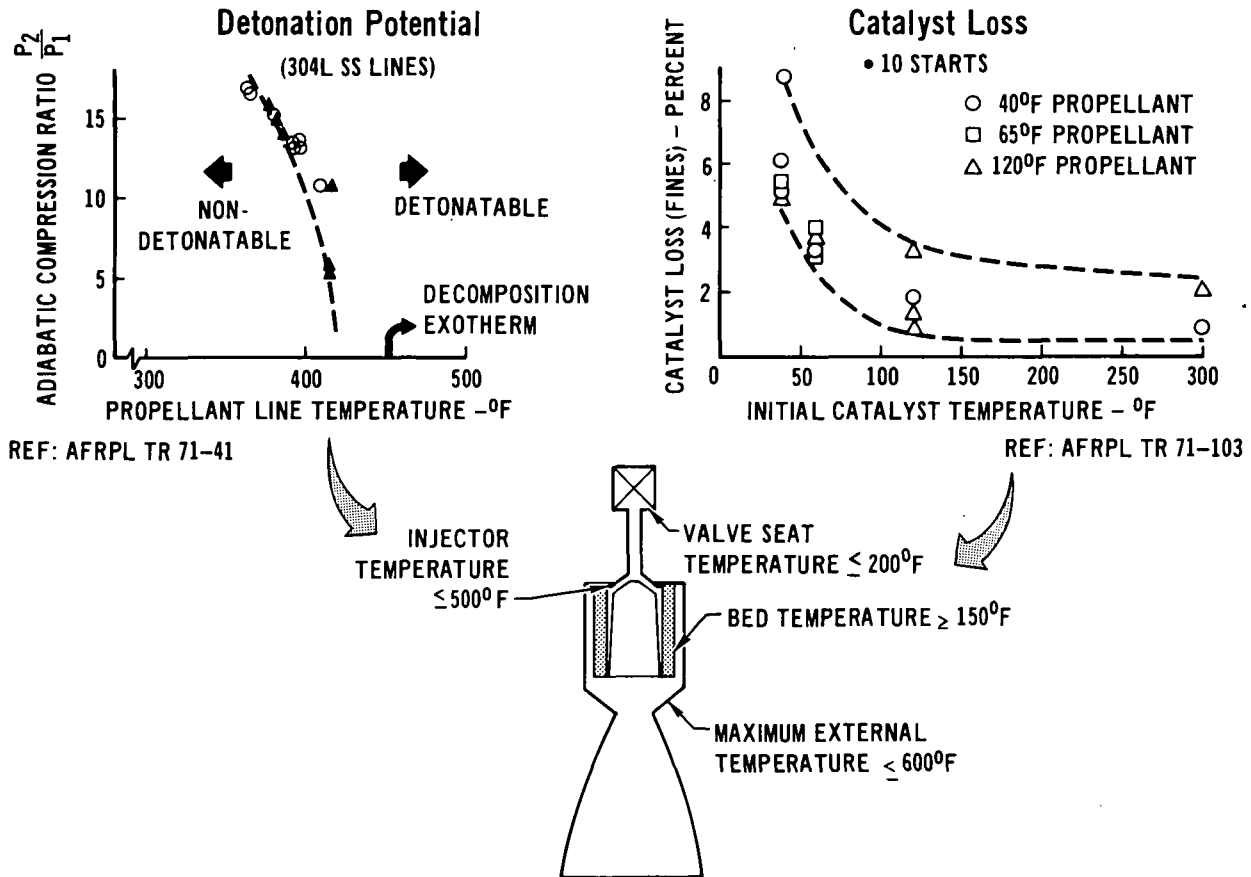


FIGURE 4-18 MONOPROPELLANT THRUSTER THERMAL CONSTRAINTS

the injector temperature rises to  $500^\circ\text{F}$  when uncontrolled. With the heat pipe, the injector temperature rise is reduced and it is cooled more rapidly. The problem is more severe, however, when multiple firings occur. For this case (Figure 4-19), soakback continued for 2000 seconds. At that time, it was assumed that a second pulse occurred in which the thruster and catalyst temperatures were elevated to the steady state firing conditions. With a heat pipe system, the injector temperature does not exceed the  $500^\circ\text{F}$  maximum injector temperature. For the uncontrolled system using only the capacitance of the module and the thruster mounting plate, however, the injector temperature rises to about  $560^\circ\text{F}$ , well above the allowable limit. These thruster-module-ECLS calculations indicate that satisfactory operation can be achieved by linking the module to the ECLS with heat pipes.

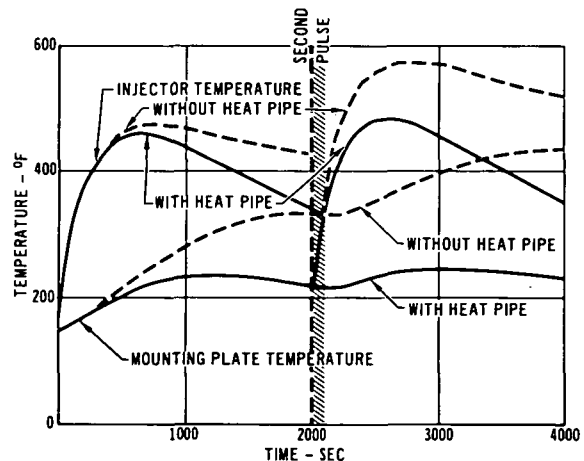


FIGURE 4-19 EFFECT OF PULSE OPERATION ON THRUSTER TEMPERATURE TRANSIENTS

Steady state and transient thermal responses have been examined for the fuselage mounted module. Maximum uncontrolled propellant temperatures (115°F) were somewhat less than for the wing tip pod because of additional communication with the vehicle. However, heater power levels required to maintain minimum temperatures were substantially higher, due to the increased tank size and reduced thermal communication with earth. Tank structure and support transients have been examined to evaluate techniques for reducing the principal leaks. Tank support was provided by aluminum structure cantilevered from the fuselage side. In this configuration there is no conduction heat transfer from the tank to the thruster enclosure, and the thruster enclosure serves as a radiation shield between the tanks and space. The results show that to maintain 40°F conditions for the four tanks in a module subjected to a cold environment requires an

input of 330 watts.

**4.4 Concepts Comparison** - System sizing analyses were performed for the candidate configurations. Optimal design points were determined by generating system weight sensitivities to chamber pressure, expansion ratio, and mixture ratio (for bipropellant systems), as presented in Figure 4-20 for the modular bipropellant RCS. As shown, the expansion ratios of the -X translational thrusters have been optimized as an independent parameter. This results in a significant weight savings for the RCS(OMS); the savings realized by the remaining systems are minimal and would not warrant the use of a different expansion ratio. Pod structure and thermal protection weight drives the optimum modular RCS design points to low expansion ratio and high chamber pressure (both favoring smaller thrusters and therefore smaller pods).

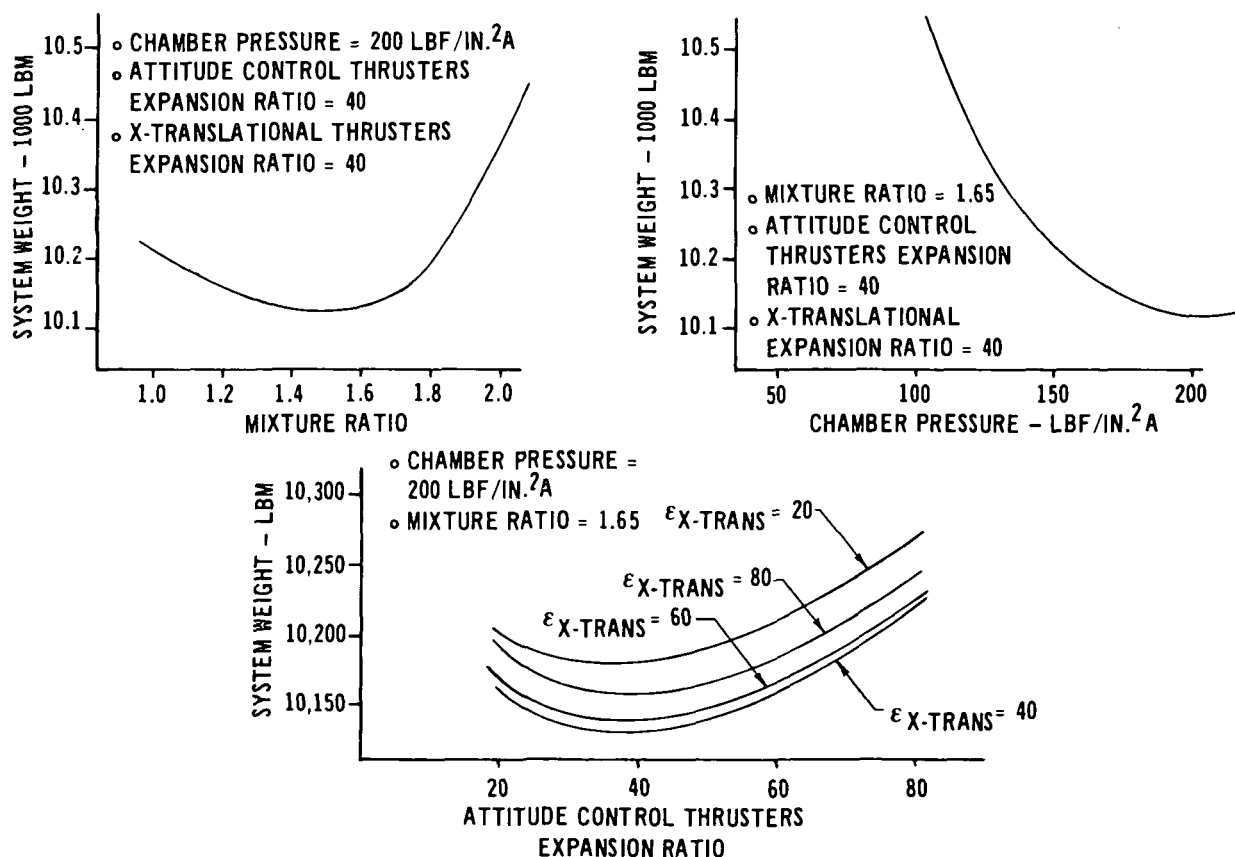


FIGURE 4-20 SYSTEM WEIGHT SENSITIVITIES  
Modular RCS-NTO/MMH

Figure 4-21 summarizes the optimal design parameters and system weights. In order to provide a common ground for weight comparison, a total propulsion system weight comprised of the applicable RCS, OMS, and APU weight is included. The evaluation of a dedicated OMS was not a part of this study. However, in order to properly compare the alternate concepts, a generic OMS was necessary. The OMS weight was derived from the Orbit Maneuvering System Trade Studies (Contract NAS 9-12755).

When comparing system weights, it is necessary to differentiate between system expendables weight, which has a 1:1 tradeoff with payload, and system inert weight, which reduces payload by 1.4 lb for each pound in-

crease. Thus, the proper method of comparing systems is on the basis of payload penalty. Comparisons on the basis of payload magnify the weight penalty associated with modularized system concepts. Figure 4-22 presents the relative payload weights. Comparison of the candidate configurations reveals the following:

- 1) The lightest system approach is realized with an integral, bipropellant RCS/OMS and a modular monopropellant APU.
- 2) The payload penalty for modularizing the bipropellant RCS and OMS is 2184 lbm.
- 3) The modularized, bipropellant RCS(OMS) is almost 1300 lbm heavier (on a payload basis) than the combined weight of a modularized RCS and modularized OMS.

SYSTEM	DESIGN SUMMARY	OPTIMAL DESIGN PARAMETERS							
		RCS IMPULSE	F	P <sub>TANK</sub>	P <sub>c</sub>	ε	MR	I <sub>sp</sub>	WEIGHT
MODULAR RCS (MONOPROPELLANT)	WING AND NOSE MODULES HELIUM PRESSURIZATION TITANIUM TANKAGE SURFACE TENSION POSITIVE EXPULSION CONVENTIONAL NOZZLE THRUSTERS	1,831,810	600	312	150	20 (ATT CONT) 20 (- X)	-	228.8 (ATT CONT) 228.8 (- X)	12,889 (12,889 - RCS) ( 3,295 - APU) <u>(28,790 - OMS)*</u> 44,974
MODULAR RCS (BIPROPELLANT)	WING AND NOSE MODULES HELIUM PRESSURIZATION TITANIUM TANKAGE SURFACE TENSION POSITIVE EXPULSION FILM COOLED THRUSTERS	1,831,810	600	368	200	40 (ATT CONT) 40 (- X)	1.65	296.1 (ATT CONT) 296.1 (- X)	10,133 (10,133 - RCS) ( 3,295 - APU) <u>(28,790 - OMS)*</u> 42,218
MODULAR RCS (OMS) (BIPROPELLANT)	FUSELAGE AND NOSE MODULES HELIUM PRESSURIZATION TITANIUM TANKAGE SURFACE TENSION POSITIVE EXPULSION FILM COOLED THRUSTERS	1,973,464 (RCS) 7,831,849 (OMS)	600	250	150	60 (ATT CONT) 80 (- X)	1.65	299.1 (ATT CONT) 306.2 (- X)	40,155 (40,155 - RCS (OMS)) ( 3,295 - APU) <u>43,410</u>
INTEGRATED RCS/OMS (BIPROPELLANT)	COMMON TANKAGE LOCATED BELOW PAYLOAD BAY HELIUM PRESSURIZATION TITANIUM TANKAGE SURFACE TENSION POSITIVE EXPULSION FILM COOLED THRUSTERS	1,899,678 (RCS) 7,841,338 (OMS)	600	250	150 (RCS) 150 (OMS)	60 (ATT CONT) 60 (- X)	1.65	299.1 (ATT CONT) 299.1 ( X) 315.9 (OMS)	37,360 (37,360 - RCS/OMS) ( 3,295 - APU) <u>40,655</u>
INTEGRATED RCS/APU (MONOPROPELLANT)	COMMON TANKAGE LOCATED BELOW PAYLOAD BAY HELIUM PRESSURIZATION (RCS) BOOST PUMP PRESSURIZATION (APU) SURFACE TENSION POSITIVE EXPULSION CONVENTIONAL NOZZLE THRUSTERS ACTIVE, ACTIVE, IDLE, DORMANT APU REDUNDANCY WATER COOLED APU	1,899,678	600	272	125 (RCS) 1000 (APU)	40 (ATT CONT) 40 (- X)	-	235.4 (ATT CONT) 235.4 (- X)	14,586 (14,586 - RCS APU) <u>(28,790 - OMS)*</u> 43,376
MODULAR APU (MONOPROPELLANT)	AFT FUSELAGE MODULES HELIUM PRESSURIZATION TITANIUM TANKAGE SURFACE TENSION POSITIVE EXPULSION ACTIVE, ACTIVE, IDLE, DORMANT APU REDUNDANCY WATER COOLED APU	-	-	766	500	-	-	-	3,295

\* OMS SPECIFIC IMPULSE = 313 SEC

FIGURE 4-21 DESIGN POINT SUMMARIES

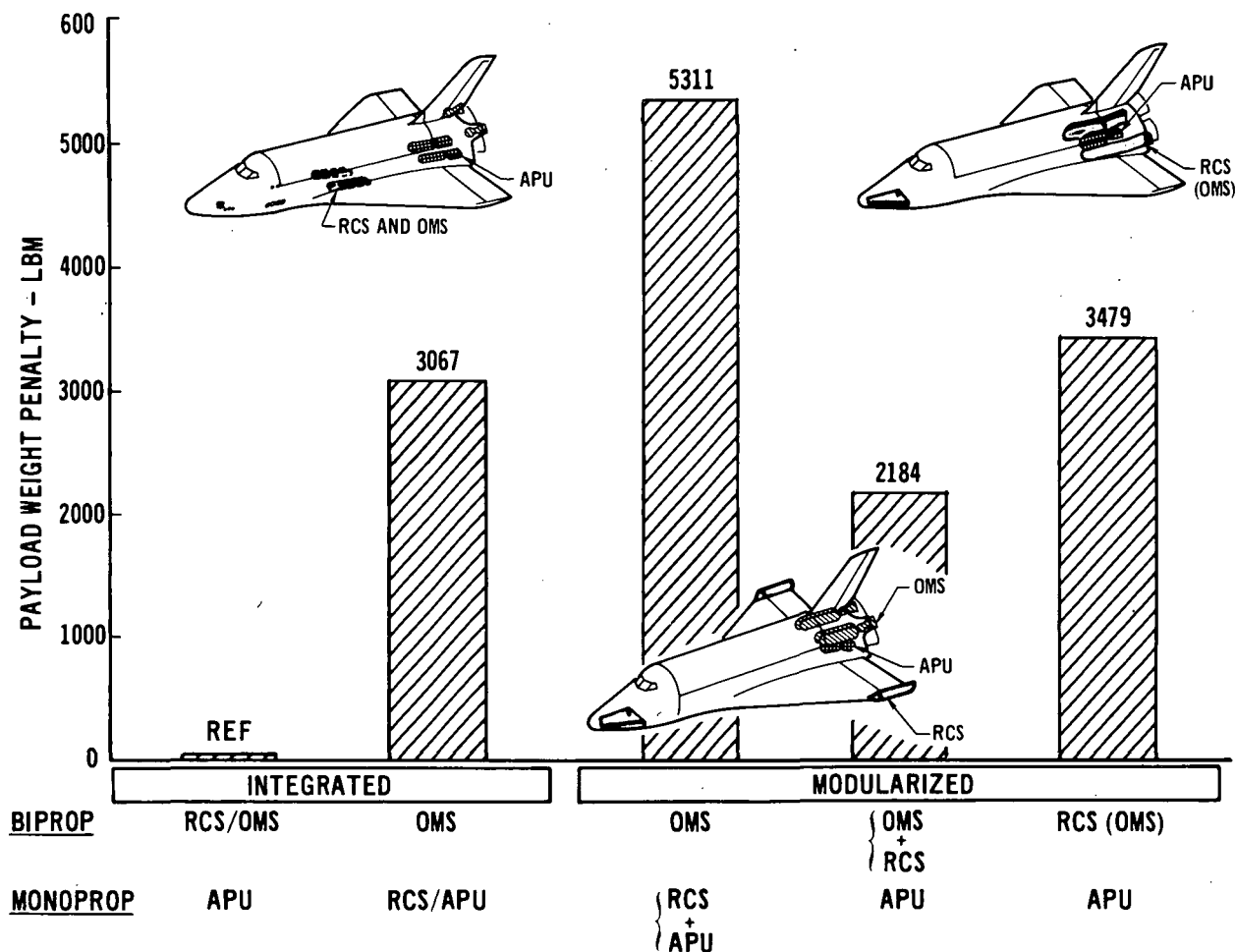


FIGURE 4-22 RELATIVE PAYLOAD WEIGHTS

- 4) The modularized monopropellant RCS has a reduced payload of 3130 lbm when compared with the modularized bipropellant RCS.

Each configuration is the result of an individual optimization; tankage and thruster locations have been separately established, and design points defined consistent with the particular requirements of each system. These final comparisons are therefore considered to be realistic evaluations of the alternate configurations. One significant advantage afforded by integral systems is weight, but the maintenance complications associated with integral systems are unacceptable for a reusable vehicle. Consequently, only modular systems can be seriously considered for use on Shuttle.

As discussed in Section 1, the objective of this study was to develop design and programmatic data for competitive reaction control systems in sufficient detail that a selection can be made between the various concepts. In keeping with this objective, the concluding effort in this study was an assessment of the weight implications of selected configuration changes on the design point weights. The effects of changes in pressurization concept, type of tank expulsion, and tank material are shown in Figure 4-23 for the modular bipropellant RCS. Weight savings are possible in the area of pressurization, with the largest savings available for the high impulse configurations (modular RCS(OMS) and integrated RCS/OMS). In

general, the pump fed pressurization concept offers the largest savings; however, its adoption results in increased system complexity. By contrast, the savings afforded by composite pressurant tanks reflect no decrease in system reliability. Additionally, composite tanks generally provide a leakage failure mode

rather than fracture. The weight penalties associated with system redundancy are also presented to allow evaluation of the weight penalty associated with the fail safe/fail safe redundancy philosophy. The weight savings shown represent the elimination of all components except those necessary for completion of a failure free mission.

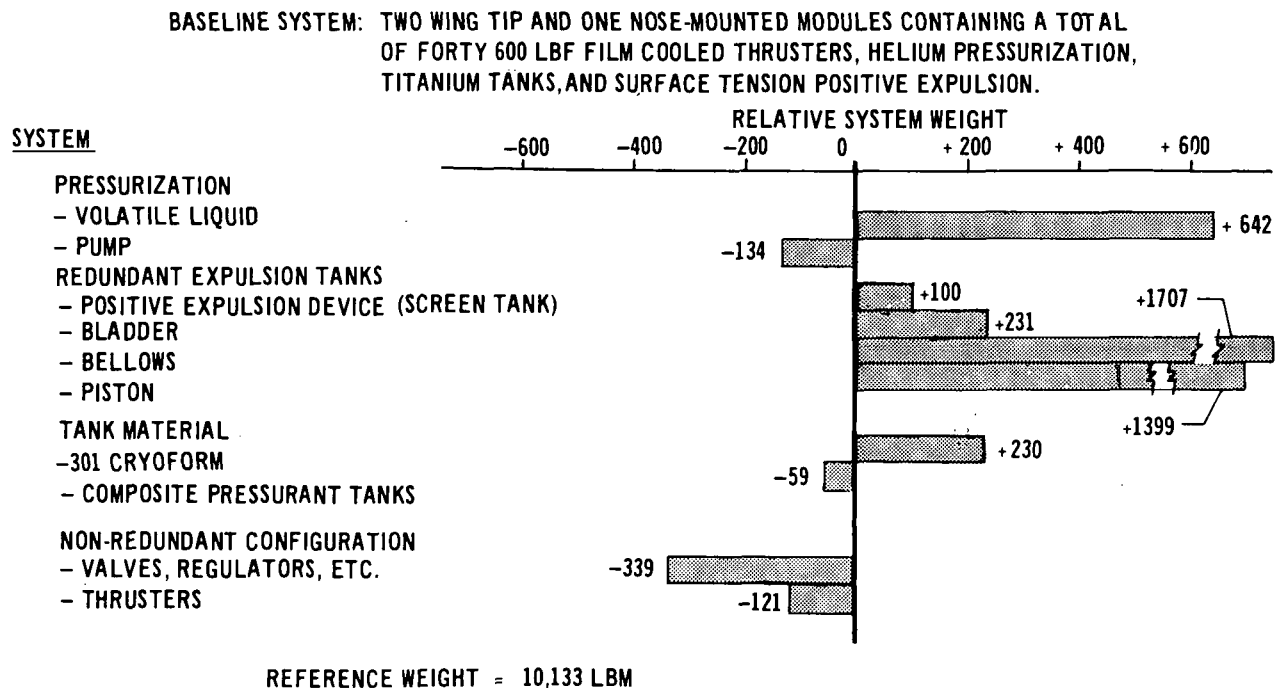


FIGURE 4-23 WEIGHT RELATIVE TO BASELINE MODULAR RCS (N<sub>2</sub>O<sub>4</sub>/MMH)

As originally defined, Phase E was to be a final performance analysis of the six systems described above. However, prior to the completion of this evaluation, North American Rockwell (NR) was awarded the Space Shuttle Orbiter prime contract by NASA. The NR shuttle configuration employs a dedicated bipropellant OMS and a monopropellant RCS installed in fuselage and nose modules. The RCS utilizes 40 thrusters of 1000 lbf each. Common size propellant and pressurant tanks are used in the nose and fuselage modules. In order to maximize the utility of the APS study results, additional

analysis was performed to further study the fuselage module options. Five alternate fuselage configurations were evaluated:

1. Dedicated OMS, common RCS-OMS tankage
2. Common RCS-OMS thrusters, common tankage (the RCS(OMS) of Phase E)
3. Dedicated OMS, dedicated tankage (bipropellant RCS)
4. Common RCS-OMS thrusters, dedicated tankage
5. Dedicated OMS, dedicated tankage (monopropellant RCS)

The design points, shown in Figure 4-24, for these alternate fuselage configurations were established by analogy to the Phase E systems. Common tankage contains RCS and OMS propellants jointly, whereas dedicated tankage provides separate tankage for the two functions. The use of dedicated tankage for the OMS function profits from the fact that full-tank surface tension acquisition is not required for the large tanks, since a small screen trap is sufficient.

A comparison of relative payload penalties for the five concepts is presented in Figure 4-25. This figure reflects a 1:1 tradeoff between system expendable weight and payload decrease, and a 1:1.4 tradeoff between system inert weight and payload decrease. Comparison of these systems reveals the following:

1. Minimum vehicle weight is provided by the concept employing a dedicated OMS and dedicated tankage.
2. A 2700 lbm payload penalty is associated with the use of a monopropellant RCS, as opposed to a bipropellant RCS.

3. The use of RCS thrusters for all maneuvers results in a 750 lbm payload penalty, referenced to the minimum weight system.
4. Dedicated tankage is the preferred choice for the RCS(OMS) configuration, since weight differences are minimal.

The final comparison of interest concerns the fuselage mounted bipropellant RCS concept (configuration No. 3) described above, and the wing mounted bipropellant modular RCS concept. The wing module configuration is approximately 300 lbm lighter. This difference is minimal, and therefore definition of the more attractive concept must certainly consider additional parameters, such as maintainability.

Additional evaluation of the candidate configurations with regard to operational, maintenance, and safety considerations was performed. The objective was to determine what advantages or disadvantages are associated with various classes of systems, thereby allowing general comparisons to be made, e.g., monopropellant vs bipropellant, integral vs modular.

POD DESIGN CHARACTERISTICS				SYSTEM DESIGN POINTS													
RCS/OMS TANKAGE	PROPELLANTS		RCS/OMS ENGINES	THRUST		CHAMBER PRESSURE		TANK PRESSURE		EXPANSION RATIO			MIXTURE RATIO		SPECIFIC IMPULSE		
	RCS	OMS		RCS	OMS	RCS	OMS	RCS	OMS	RCS	+X RCS	OMS	RCS	OMS	RCS(1)	X RCS	OMS
COMMON	N <sub>2</sub> O <sub>4</sub> /MMH	N <sub>2</sub> O <sub>4</sub> /MMH	DEDICATED	600	6000	150	150	249	249	60	60	90	1.65	1.65	299.1	299.1	315.9
COMMON	N <sub>2</sub> O <sub>4</sub> /MMH	N <sub>2</sub> O <sub>4</sub> /MMH	COMMON	600	600	150	150	249	249	60	90	-	1.65	1.65	299.1	306.2	-
DEDICATED	N <sub>2</sub> O <sub>4</sub> /MMH	N <sub>2</sub> O <sub>4</sub> /MMH	DEDICATED	600	6000	175	125	285	205	60	60	75	1.65	1.65	299.3	299.3	313.5
DEDICATED	N <sub>2</sub> O <sub>4</sub> /MMH	N <sub>2</sub> O <sub>4</sub> /MMH	COMMON	600	600	150	150	249	249	60	90	-	1.65	1.65	299.1	306.2	-
DEDICATED	N <sub>2</sub> H <sub>4</sub>	N <sub>2</sub> O <sub>4</sub> /MMH	DEDICATED	600	6000	125	125	235	205	40	40	75	-	1.65	235.3	235.3	313.5

(1) USE 76% I<sub>sp</sub> (SS) FOR PULSING

FIGURE 4-24 DESIGN POINT SUMMARY



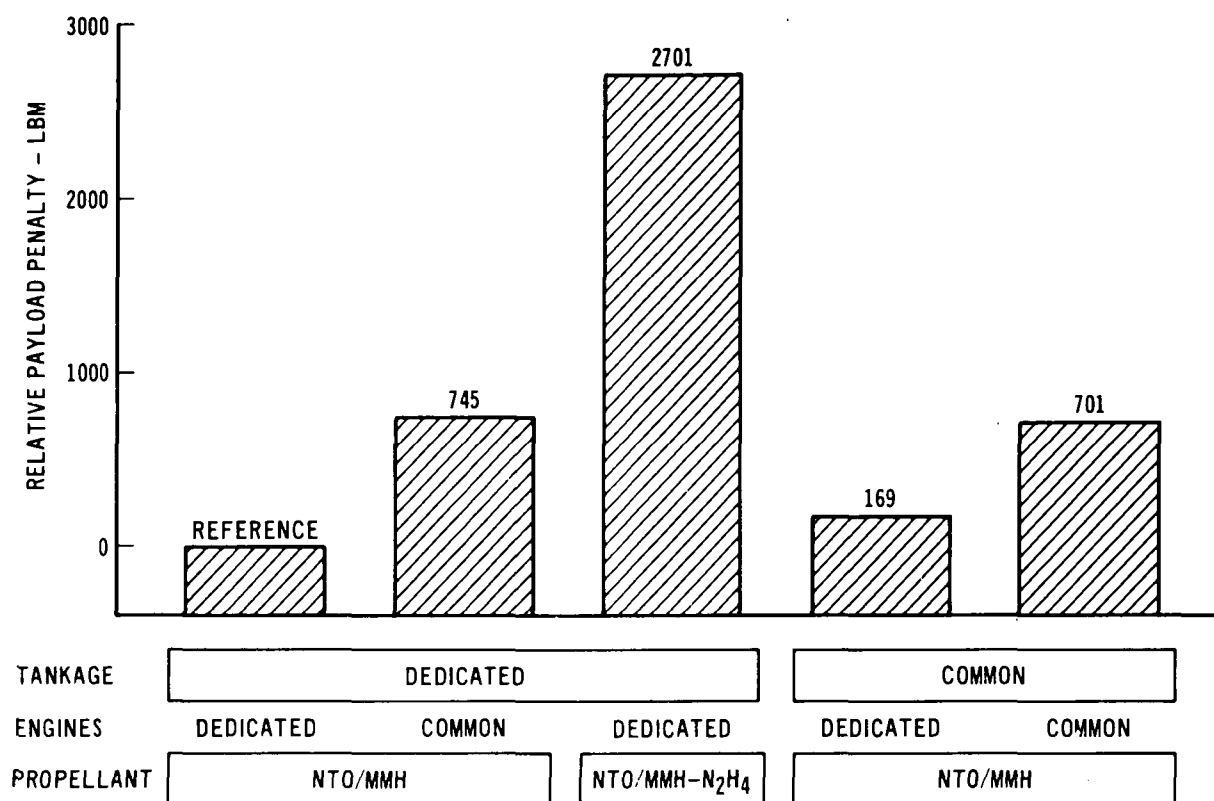


FIGURE 4-25 COMPARATIVE PAYLOAD PENALTIES FOR CANDIDATE TANK/ENGINE SYSTEMS

**4.5 Reusability Effects - Propellant handling considerations** have a considerable influence on earth storable system designs. Due to the toxicity, corrosiveness and, in the case of bipropellants, hypergolic nature of the propellants, safety considerations dictate that only those personnel directly involved in RCS servicing be allowed in the proximity of the system during these operations. For a system that is installed integrally within the vehicle, this constraint would force vehicle maintenance operations to be conducted serially, and would extend the vehicle turnaround time by approximately two days. To meet the Shuttle objective of a two week turnaround, attention has focused on the use of removable, self-contained modules. The modules would be removed from the vehicle after landing and taken to a remote facility suitable for safe maintenance and filling operations. Vehicle maintenance could then proceed without

elaborate precautions. The following discussion defines the anticipated maintenance procedures, assuming a modularized propulsion system.

The major portion of the system will remain "wet" but it is considered necessary to purge dry the thruster assemblies for safety and reuse. System safing will begin during re-entry, following vehicle transition to airplane mode of flight. At this time, propellant isolation valves will be closed and the thruster assemblies purged with residual helium pressurant.

Figure 4-26 summarizes the ground safing and servicing requirements. After vehicle landing and cooldown, system depressurization will be verified and a nitrogen purge of the thrusters will be performed to assure that all propellants have been cleared. System power will then be removed and thruster throat plugs will be installed.

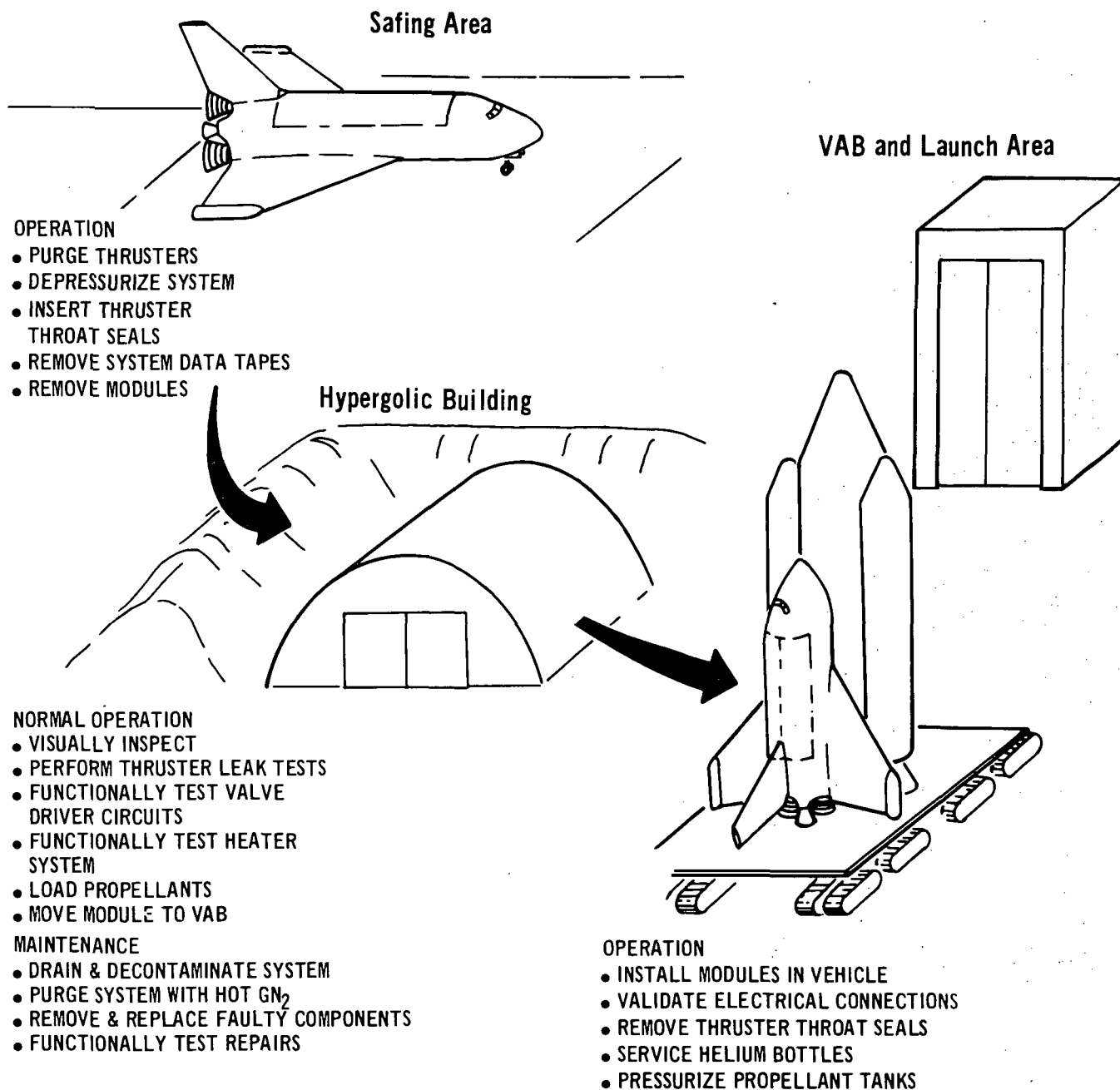


FIGURE 4-26 GSE REQUIREMENTS

Propulsion modules will be removed to a remote facility for servicing. Normal servicing will include such operations as testing valve driver circuits and the heater system and performing leak checks. The tanks and control components will be maintained wet to the maximum extent possible. Gravity fill procedures will be employed, and propellant quantities determined by weight (modules removed) or by overfilling and metering off the required ullage volume (modules installed).

Maintenance operations will be performed based on inflight checkout intelligence data. Failure probability analyses show that the required system repair frequency will be high. As shown in Figure 4-27, estimates vary from a propellant system failure every 1 to 3 flights for a bipropellant RCS and a propellant system failure every 1 to 5 flights for a monopropellant RCS. These numbers illustrate the importance of component accessibility in reducing maintenance downtime. A review of component failure data from previously flown spacecraft has indicated that the primary cause of failure is contamination, and the components most susceptible to contamination are the pressurant check valves and the propellant valves. System reliability and reusability would be benefited by maintaining the propellant feed system in a wetted condition.

The replacement of propellant system components other than thrusters and pressurization components would require either complete or partial system draining and flushing to remove residual propellants from the system in order to assure a safe environment for maintenance personnel. Of the various cleaning methods available, the single-flush method and the vapor-phase flush method, in which the solvent is introduced into the system in its vapor phase, appear to be the most promising approaches for decontamination of the shuttle RCS when necessary. A review of available solvents has identified Isopropanol and Freon TF as the most attractive solvents for fuel and oxidizer systems, respectively.

Several conclusions regarding reuse are applicable regardless of the configuration chosen. The successful implementation of a multi-mission vehicle will require thorough consideration of reusability throughout system design, including the establishment of thermal control requirements consistent with reusability, and in the definition of servicing, safing and maintenance operating procedures. The safety and reuse criteria identified in this study have been so categorized, and are summarized in Figure 4-28. Reuse considerations necessitate added care in the selection of component types and arrangement to minimize the generation and effects of contaminants on system operation.

SUBSYSTEM ASSEMBLY	MONOPROPELLANT MISSIONS	BIPROPELLANT MISSIONS
TOTAL RCS	1.0 —→ 4.7	0.7 —→ 2.9
TOTAL RCS LESS INSTRUMENTATION	1.4 —→ 6.6	0.9 —→ 3.7
RCS INSTRUMENTATION	4.1 —→ 16.5	3.5 —→ 14.3
PRESSURIZATION COMPONENTS	10.4 —→ 57.3	5.0 —→ 25.3
PROPELLANT STORAGE AND CONTROL	6.5 —→ 52.0	4.1 —→ 31.8
PROPELLANT TANKS & FILL VALVES	19.1 —→ 187.0	23.4 —→ 224.0
THRUSTER ASSEMBLIES	2.1 —→ 8.8	1.4 —→ 5.0

**FIGURE 4-27 MEAN TIME BETWEEN COMPONENT FAILURE**  
**Modular RCS**

## Design

- PROVIDE SYSTEM ACCESS WITH VEHICLE IN EITHER HORIZONTAL OR VERTICAL (LAUNCH) ATTITUDE
- EMPLOY INTERLOCKS OR OTHER SAFEGUARDS ON MANUAL VALVES TO ASSURE VALVES ARE IN FLIGHT POSITION PRIOR TO LIFT-OFF
- USE SEPARATE PRESSURANT SUPPLIES FOR FUEL AND OXIDIZER
- DESIGN FOR FAIL-SAFE, FAIL-SAFE REDUNDANCY OR BACK-UP CAPABILITY ON ALL ACTIVE COMPONENTS
- USE COMPOSITE (OVER WRAP) PRESSURANT TANKS TO ASSURE TANK FAILURE IS BY LEAKAGE RATHER THAN FRACTURE
- EMPLOY FLEXIBLE PROOF TEST FACTORS ON PRESSURE VESSELS, ADJUSTING FOR TANK MATERIAL ENVIRONMENT, HOOP LOADS AND REQUIRED LIFE. PROOF TEST WITH LIQUID NITROGEN TO REDUCE REQUIRED PROOF PRESSURE LEVELS AND/OR TO VERIFY GREATER CYCLE LIFE FOR GIVEN DESIGN SAFETY FACTOR
- USE MATERIALS THAT ARE COMPATIBLE WITH PROPELLANTS AND RESIDUES FORMED BY PROPELLANT REACTION WITH THIRD AGENTS, I.E.,  $H_2O$ ,  $CO_2$ , SOLVENTS, ETC
- PROVIDE REPLACEABLE COMPONENT CARTRIDGES FOR HIGH FAILURE RATE ITEMS
- USE BREAKABLE SEALS BETWEEN MONOPROPELLANT THRUSTER AND THRUSTER VALVES TO FACILITATE CATALYST REPLACEMENT

## Thermal Control

- THERMALLY CONTROL TO FOLLOWING TEMPERATURE CONSTRAINTS:

	(°F)
$N_2H_4$ THRUSTER	CATALYST > 150 (CATALYST LIFE)
	INJECTOR < 500 (DETONATION POTENTIAL)
	VALVE < 200 (SEAT LIFE)
$N_2O_4$ /MMH THRUSTER	INJECTOR > 70 (IGNITION PRESSURE SPIKING)
	VALVE < 200 (SEAT LIFE)
PROPELLANTS	$N_2H_4$ > 50 (FREEZING)
	$N_2O_4$ /MMH > 40 (IGNITION PRESSURE SPIKING/ $N_2O_4$ FREEZING)

## Safing and Maintenance

- PERFORM POST-DEACTIVATION FLIGHT PURGE OF THRUSTER ASSEMBLIES
- DEPRESSURIZE SYSTEM FOR GROUND SERVICING AND/OR POD TRANSPORT
- INSERT THRUSTER THROAT SEALS AFTER LANDING
- MAINTAIN WET TANK AND CONTROL COMPONENTS TO MAXIMUM PRACTICAL EXTENT. WHEN NECESSARY, FLUSH SYSTEM WITH VAPORIZED SOLVENTS (FREON TF-NT0; ISOPROPANOL - MMH,  $N_2H_4$ ) FOLLOWED BY HOT  $GN_2$  PURGE. PULSATE FLOW OF GASIFIED SOLVENTS TO SCAVENGE PROPELLANT VAPORS).
- PROVIDE CLOSED-VENT SYSTEM FOR PROPELLANT DUMP
- AVOID AIR DRY OF EPT RUBBER EXPULSION BLADDERS

## Servicing

- UTILIZE MOLECULAR SIEVES TO REMOVE SOLUBLE IRON FROM  $N_2O_4$  PROPELLANT DURING FILL OPERATIONS (MINIMIZE RHEOPEXY POTENTIAL)
- EMPLOY GRAVITY FILL PROCEDURES FOR PROPELLANT SERVICING
- AVOID BACKFILL THROUGH SCREEN SURFACE TENSION TANKS TO AVOID SCREEN LOADING IN UNSUPPORTED DIRECTION
- AVOID PROPELLANT TEMPERATURE CONDITIONING DURING FILL. VERIFY PROPELLANT LOAD BY COMPLETELY FILLING TANKS AND OFF-LOADING ULLAGE

FIGURE 4-28 SAFETY AND REUSE CRITERIA

## 5. STUDY CONCLUSIONS

Candidate oxygen/hydrogen propellant auxiliary propulsion systems were compared on the basis of weight, technology, simplicity, flexibility, and reusability. Three oxygen/hydrogen turbopump RCS configurations were evaluated with respect to operational characteristics and controls requirements. All three configurations were judged to be competitive, with the series-downstream turbine RCS offering a slight advantage. Technology concerns associated with this class of system include a high conditioner cycle life requirement and excessive turbopump shaft accelerations.

On the basis of weight, the most attractive system was an oxygen/hydrogen system in which the propellants are delivered to the thrusters as liquids. In addition, this system concept escapes the conditioner life and turbopump shaft acceleration technology concerns associated with the oxygen/hydrogen turbopump RCS.

A change in orbiter design during the study reduced RCS impulse requirements and promoted renewed interest in earth storable propellant systems. Figure 5-1 shows that, even at smaller orbiter impulse levels, a storable system weighs on the order of 3,000 to 5,000

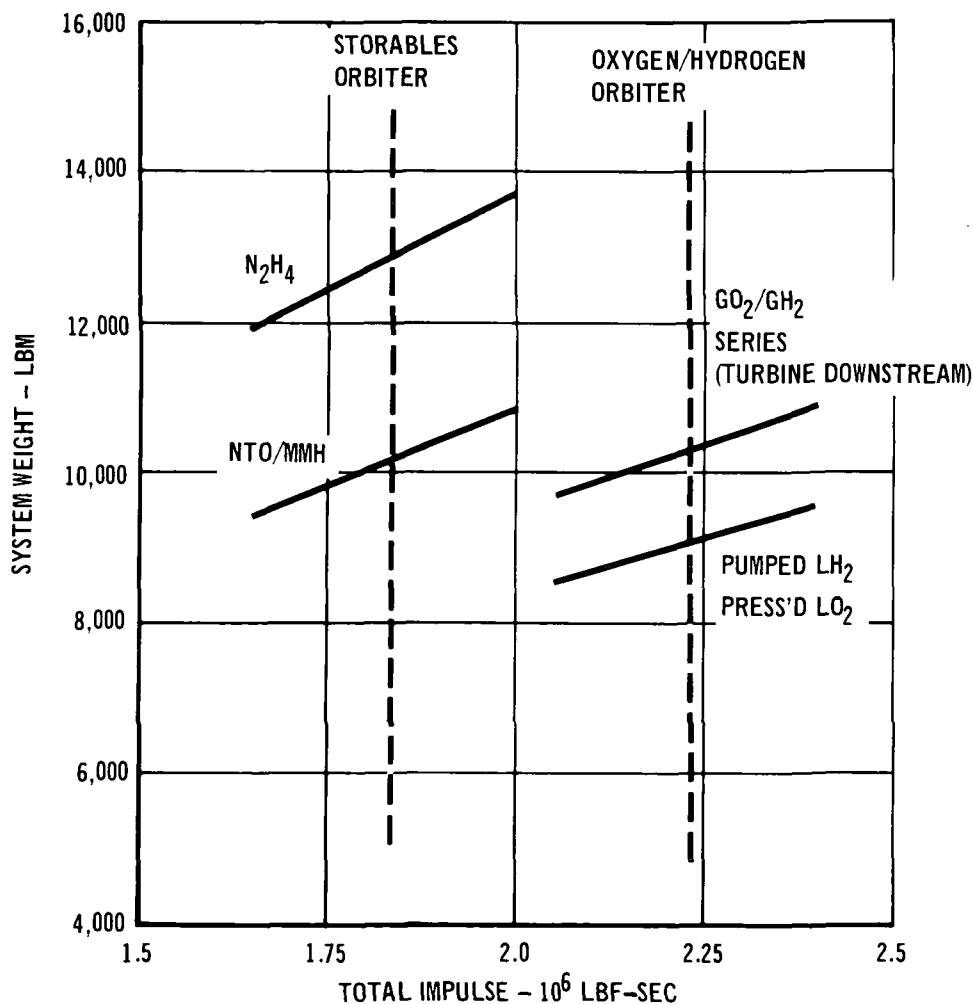


FIGURE 5-1 COMPARISON OF MODULAR STORABLE RCS CONCEPTS  
WITH INTEGRAL CRYOGENIC RCS CONCEPTS

lbm more than a liquid-liquid oxygen/hydrogen system. However, the reduced volume of the smaller orbiter does not allow use of an oxygen/hydrogen OMS. This weight difference could not justify the high cost and technology risk associated with the development of an oxygen/hydrogen RCS alone. Thus, earth storable propellant systems were selected for the RCS and oxygen/hydrogen propellants were eliminated from further consideration.

Three basic storable propellant concepts were defined: a modular concept utilizing wing and nose modules, a modular concept utilizing fuselage and nose modules, and a non-modular concept wherein the RCS was in-

tegral with the vehicle. For each concept, alternate configurations were defined by specifying the propellants (monopropellant or bipropellant) and either common or dedicated tankage and RCS thrusters/OMS engines.

Integral systems suffer, relative to modular systems, in the areas of safety, ease of maintenance, development flexibility, and growth potential. Although attractive from a weight standpoint, the above considerations are sufficient to eliminate integral systems from contention.

Figure 5-2 summarizes the relative advantages of wing and fuselage modular systems. No clearcut preference is evident; weights are comparable, and no significant

	WING TIP POD	FUSELAGE POD
WEIGHT	10,133 LBM	10,400 LBM
CONTROL	IMPULSE REQUIREMENTS MINIMIZED BY LARGE MOMENT ARMS. (FINE CONTROL MORE DIFFICULT TO ACHIEVE). THRUSTER LOCATIONS MINIMIZE CROSS-COUPLING	BIAS DISTURBANCE TORQUES (YAW) RESULT IN UNEQUAL PROPELLANT EXPENDITURE BETWEEN PODS FOR ON-ORBIT CONTROL
SAFETY/MAINTENANCE	POD LOCATIONS FACILITATE REMOVAL/INSTALLATION OPERATIONS. COMPONENT ACCESSIBILITY MORE DIFFICULT (PODS REMOVED) BECAUSE OF TOTAL ENCLOSURE - MORE ACCESS DOORS	POD ACCESS DIFFICULT BECAUSE OF POD LOCATION OVER THE WING. COMPONENTS EASILY ACCESSIBLE WITH PODS REMOVED
THERMAL CONTROL	UNCONTROLLED TEMPERATURE RANGE - 110°F TO +165°F. MDAC-RSI AVERAGE UNIT WEIGHT = 2.34 LBM/FT <sup>2</sup> THRUSTER HEATERS - 5.4 WATTS/THRUSTER TANK HEATERS - 140 WATTS DOORS REQUIRED OVER FWD-FACING THRUSTERS	UNCONTROLLED TEMPERATURE RANGE -120°F TO +115°F. MDAC-RSI AVERAGE UNIT WEIGHT = 1.65 LBF/FT <sup>2</sup> THRUSTER HEATERS - 5.4 WATTS/THRUSTER TANK HEATERS - 50 WATTS
AFFECT ON AERODYNAMICS	EFFECTS MINIMIZED BY • KEEPING PODS ON TOP SIDE OF WING (HYPERSONIC STABILITY) • MINIMIZING POD FRONTAL AREA (DRAG) TAPERING OF ELEVONS IS REQUIRED TO PROVIDE SUFFICIENT WING STRUCTURE FOR POD SUPPORT	EFFECTS MINIMIZED BY • MINIMIZING POD FRONTAL AREA (DRAG) • POD BOATTAIL (BASE DRAG)  MINIMAL JI EFFECTS ON CONTROL SURFACES DUE TO AFT LOCATION OF CONTROL THRUSTERS
SEVERITY OF DYNAMIC ENVIRONMENTS	UNSTEADY FLOW ON WING MAY INDUCE WING/POD RESPONSE THAT COULD RESULT IN FLUTTER HIGH ACCELERATION AND PROPELLANT SLOSH LOADS LIKELY BECAUSE OF RCS LOCATION (REMOTE FROM VEHICLE CG)	MINIMAL EFFECT ON TANKAGE DUE TO CLOSE PROXIMITY TO VEHICLE ROLL AXIS

FIGURE 5-2 WING-TIP/FUSELAGE POD COMPARISON  
Bipropellant N<sub>2</sub>O<sub>4</sub>/MMH

technology concerns impact either concept. However, the wing modules do complicate wing design, and the forward firing thruster protection doors are unattractive. These considerations, coupled with the benefits associated with the design and development of a consolidated propulsion system make the fuselage module concept the better choice.

Within a fuselage module concept, three viable configurations remain: a dedicated OMS, coupled with either a monopropellant or a bipropellant RCS, and a bipropellant RCS for all maneuvers. For each system, dedicated tankage is more attractive than common tankage due to lessened development risk. Based on the study criteria, the dedicated OMS - bipropellant RCS is the most attractive concept. However, cost considerations,

not included in this study could alter this position. The monopropellant RCS suffers a significant weight penalty, but potentially offers reduced development effort and, possibly, reduced maintenance requirements. Cost trades between reduced development costs but increased operational costs (due to the payload penalty) are necessary to define the monopropellant RCS potential. The RCS(OMS) is weight competitive with the dedicated RCS-OMS configuration and, additionally, would be less costly since it deletes the costs associated with the OMS engine development. This concept suffers in comparison to the dedicated RCS-OMS configuration solely on the basis of its reduced flexibility to future increases in translational thrust requirements, e.g., potential future high thrust requirements for ascent abort.

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